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EXPLORING NAVAL TACTICS WITH UAVs IN AN ISLAND COMPLEX USING AGENT-BASED SIMULATION

by

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June 2007

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The benefits of Unmanned Aerial Vehicles (UAV) at sea are undisputed. The amount and speed of the incoming information from a UAV, combined with its maneuverability and "time-on-task" capability, are assets to any navy. For the Greek Navy, the main local operation area is the Aegean and Ionian Sea. As Greece lies between three continents (Europe, Asia, Africa), there is a great deal of sea traffic and potential illegal activities, such as smuggling, exploitation of illegal immigrants, and possible terrorist activity. The scope of this study is to explore naval tactics with UAVs in an island complex using Agent-Based Simulation. MANA (Map Aware Non-uniform Automata) software, used in this study, provides a visual and realistic background to conduct simulations of real operations involving many different entities. This thesis demonstrates that this type of software can rapidly produce, explore and check simulated naval tactics before actual implementation. It also shows how the UAV's technology plays a key role in a search and detection operation, whereas the enemy must rely mostly on his tactics.

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EXPLORING NAVAL TACTICS WITH UAVs IN AN ISLAND COMPLEX USING AGENT-BASED SIMULATION

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ABSTRACT

The benefits of Unmanned Aerial Vehicles (UAV) at sea are undisputed. The amount and speed of the incoming information from a UAV, combined with its maneuverability and "time-on-task" capability, are assets to any navy. For the Greek Navy, the main local operation area is the Aegean and Ionian Sea. As Greece lies between three continents (Europe, Asia, Africa), there is a great deal of sea traffic and potential illegal activities, such as smuggling, exploitation of illegal immigrants, and possible terrorist activity. The scope of this study is to explore naval tactics with UAVs in an island complex using Agent-Based Simulation. MANA (Map Aware Non-uniform Automata) software, used in this study, provides a visual and realistic background to conduct simulations of real operations involving many different entities. This thesis demonstrates that this type of software can rapidly produce, explore and check simulated naval tactics before actual implementation. It also shows how the UAV's technology plays a key role in a search and detection operation, whereas the enemy must rely mostly on his tactics.

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THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

DOE	Design of Experiment
FPB	Fast Patrol Boat
MANA	Map Aware Non-uniform Automata
MOE	Measure of Effectiveness
NOLH	Nearly Orthogonal Latin Hypercube
OLH	Orthogonal Latin Hypercube
SSM	Surface-to-Surface Missile
ToT	Time-on-Task
TSP	Traveling Salesman Problem
UAV	Unmanned Aerial Vehicle
VTUAV	Vertical Take-off Unmanned Aerial Vehicle

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EXECUTIVE SUMMARY

This study uses Agent-Based Simulation to explore naval tactics involving Unmanned Aerial Vehicles (UAV) in an island complex. The scenario focuses on the actions of a Vertical Take-off UAV (VTUAV) directed to an area of interest in order to conduct search operations. The enemy has at least one Fast Patrol Boat (FPB), which is waiting in the area for a naval force to enter within its weapon range. The enemy has the advantage that the area of interest is filled with islands and hiding positions.

The goal of this research is to investigate the following:

- Effective search patterns for the VTUAV.
- The way different factors, such as speed or the expected detection range, affect the success of the mission.
- The way the geography affects the mission (area size and few islands versus many islands).
- Effective tactics that the enemy might utilize to increase its survivability.

In order to achieve the above goals, this research proceeds in two steps. The first is a screening experiment that determines which factors are important and how they contribute to the search operation. The second step is a comparison experiment, which explores three different search patterns. For this purpose, two software packages are used. Map Aware Non-uniform Automata (MANA), an Agent-Based Simulation software, is used for the experiments, and JMP is used for the statistical analysis. See Figure 1 for a snapshot view of the scenario in MANA.

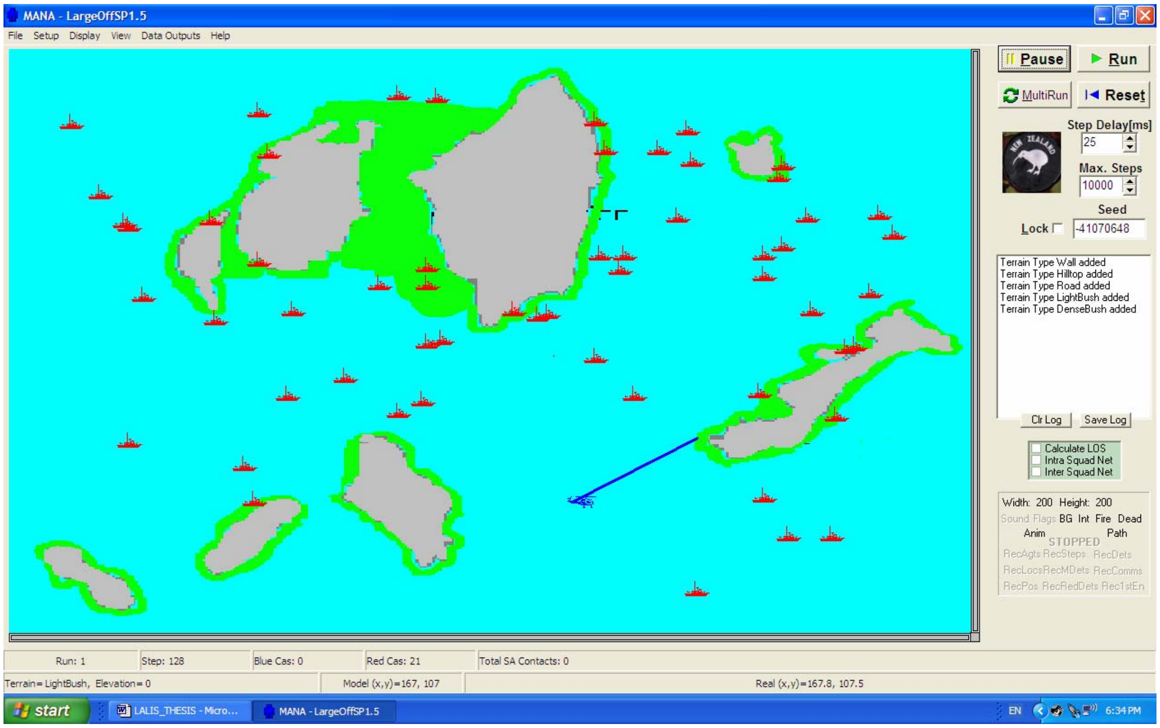

Figure 1. An instance of a MANA scenario run

The Measures Of Effectiveness (MOEs) for this two-fold research are accordingly divided into two sections. Thus, for the screening experiment, the MOE is

- The number of detected agents.

For the comparison experiment, the MOEs are

- The number of detected agents.
- The rate of detection as a means of identifying the most time-efficient search pattern.
- The number of detections for every enemy squad. This MOE could reveal a possible advantage of one squad against another and could associate some kind of tactics to this advantage.

Due to the large number of factors and their levels, a space filling Design Of Experiment (DOE) has been chosen for both the screening and comparison experiments. For the screening experiment, the Nearly Orthogonal Latin Hypercube (NOLH) design for 8-11 factors selects 33 input combinations for the numerical factors. These runs are executed for each of the eight different combinations that the categorical factors create. Thus, there are 8×33=264 simulated scenarios. Replicating 50 times each, yields 13,200 experiments.

For the screening experiment, the Orthogonal Latin Hypercube (OLH) design for 0-7 factors selects 17 input combinations for the numerical factors. These runs are executed for each of the twelve different combinations that the categorical factors create. Thus, there are 12×17=204 simulated scenarios. Replicating 50 times each, yields 10,200 additional experiments.

The basic findings are summarized for the VTUAV and the enemy separately. For the VTUAV:

- Its expected detection range and the available Time-on-Task (ToT) are critical for the success of the operation. The industry should invest in the development of better detection and identification equipment.
- While its speed is important, the analysis demonstrates that very high speeds do not dramatically improve the probability of detection. Existing VTUAV platforms can sufficiently accomplish the mission.
- The comparison between the three search patterns used reveals that they are equally effective in terms of the produced probability of detection. Thus, the only criterion needed to choose a pattern is time effectiveness. The VTUAV should visit all islands the fastest way. This might be achieved by solving a Traveling Salesman Problem (TSP).

- The VTUAV should revisit (at least) the first few islands it has searched, because the analysis shows that the enemy has better chances of surviving if it directs its course to those islands.

Regarding the enemy, the findings are as follows:

- The factors associated with the enemy's behavior have a smaller impact relative to those that explain the VTUAV's behavior.
- The enemy stands little chance of remaining undetected if the VTUAV is in its vicinity. The only technical features that can increase its survivability are its stealth and expected detection range.
- Unlike the VTUAV, the enemy should rely more on its tactics than on its technology. The enemy may effectively reach its hiding position in a stepwise movement at low speeds. The goal is to outmaneuver the VTUAV and get behind it.
- The enemy's chances of remaining undetected increase as it aims towards the first islands in the VTUAV's search pattern. Thus, these research findings suggest bold action; the FPB will be more effective if it moves toward those first islands or even the current position of the VTUAV.
- If the enemy operates in groups or is in coordination with other vessels (acting as lookouts) or troops on land, the probability of VTUAV detection decreases. With the help of an effective communication and detection network, the enemy could improve its response to the VTUAV's search operation.

In summary, this study explores the different aspects of a search operation. The intention is to show how this type of software can rapidly produce, explore and check naval tactics before they are implemented. The study also leads to rich conclusions and the possibility that future investigation topics might emerge from this research.

I. INTRODUCTION

The operations of war are operations of search.

McCue (1990)

A. SCENARIO DESCRIPTION

The benefits of Unmanned Aerial Vehicles (UAV) at sea are undisputed. The amount and speed of the incoming information from a UAV, combined with its maneuverability and “Time-on-Task” capability, are assets to any navy. For the Greek Navy, the main local operation area is the Aegean and Ionian Sea. As Greece lies between three continents(Europe, Asia, Africa), there is a great deal of sea traffic and potential illegal activity, such as smuggling, exploitation of illegal immigrants, and possible terrorist activity. These seas make distinctive and interesting study foci because they abound with islands (see Figure 2). This creates a difficult environment for sea operations and gives enemies many hiding opportunities. Questions concerning the usefulness of UAVs in such a situation, tactics of effective searches, and the characteristics of robust searches are just some of the avenues for research regarding this complex environment.

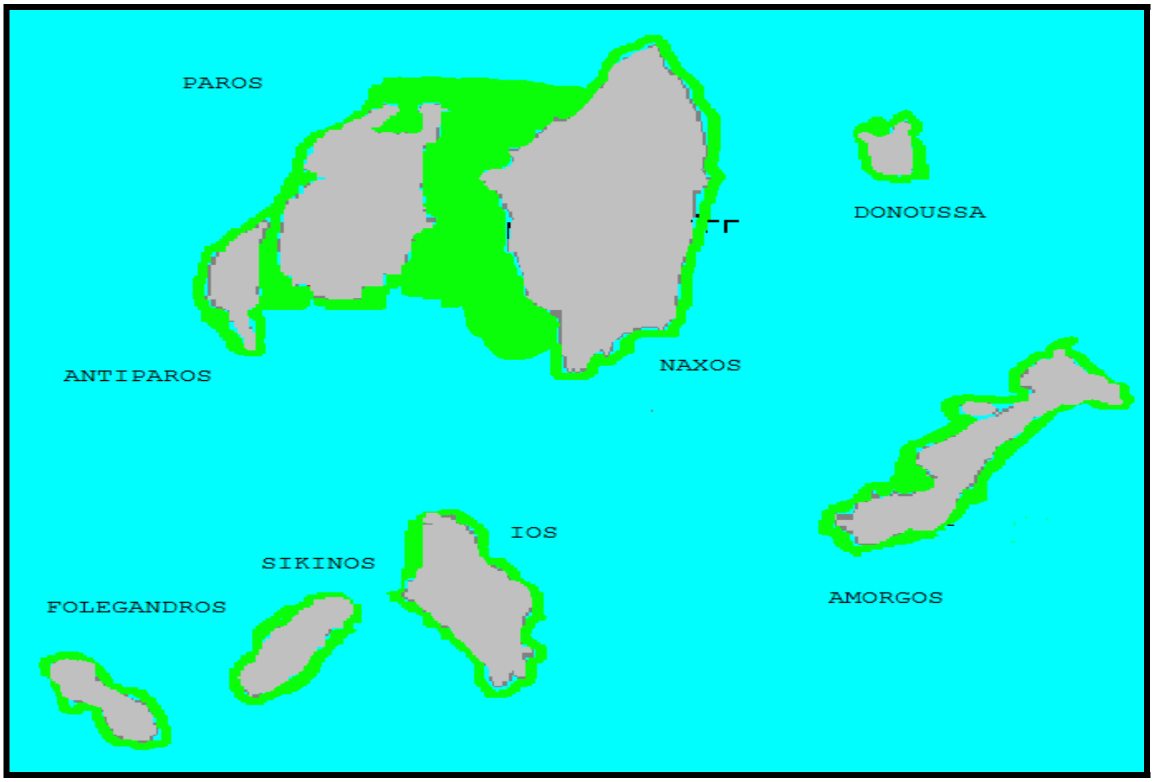

Figure 2. A modified image of an approximately 90×60 nm area of the Aegean Sea (GPSS maps)

At present, our computer technology allows us to simulate these kinds of situations so that we can gain insights with little cost. One of the latest tools is MANA (Map Aware Non-uniform Automata), an Agent-Based Simulation software that has been successful in many applications (Cioppa, Sanchez, and Lucas, 2002).

In order to reach some reasonable conclusions and insights, this research posits the following scenario: A naval force is approaching an island complex (like the Cyclades Islands in the Aegean Sea) and must secure its passage through it. The Naval Commander possesses at least one Vertical Take-off UAV (VTUAV) that can detect the presence of an unknown enemy in the area of interest. The naval force anticipates that this possible enemy includes at least one fast patrol boat (FPB), either lurking or moving inside the island complex in wait for closer proximity to the naval force, in which case the enemy can attack with Surface to Surface Missiles (SSMs).

The VTUAV’s mission is to fly over the area in such a way as to maximize detection of enemy units. There is no need to model what happens after detection; a possible enemy presence triggers a different series of actions. The enemy tries to stay “invisible”, sailing close to the islands’ shores and hoping that the naval force will enter its fire range, which may happen if the VTUAV completes its mission without detecting the FPB.

B. SCENARIO ASSUMPTIONS

Any scenario must have some assumptions in order that it can be framed in terms of time and space. For the purpose of this study, the assumptions are as follows:

1. For the Naval Force

- The force is deploying the VTUAV from a secured range. It will not approach the island complex before the air asset completes its mission.
- The geography does not have any impact on VTUAV-mother ship communication. However, geography does affect the VTUAV’s capability of detecting and identifying a target.
- The VTUAV cannot be shot down. If this happened in an actual mission, the enemy fire would instantly reveal the hostile presence in the area.

2. For the Enemy

- The enemy’s objective is to select one of the islands and use it as a hiding place until the naval force enters its weapon range.
- The enemy already waits in the island complex.
- The enemy is aware of the presence of the naval force and expects a possible UAV mission.
- The enemy cannot engage the naval force before the UAV ends its mission.

C. TECHNICAL INFORMATION

1. VTUAV Characteristics

The VTUAV, which is under consideration, is the NORTHROP-GRUMMANN FIRE SCOUT (Naval Technology, 2007). There are two possible versions, the RQ-8A and the MQ-8B. The MQ-8B is a more recent model than the RQ-8A. The basic difference between the two versions is that MQ-8B has more ToT capability.

Figure 3. The fire scout

Table 1, below, lists the technical characteristics of the VTUAV:

Table 1. Technical characteristics of the Fire Scout (Naval Technology, 2007)

PERFORMANCE	
Maximum Speed	Over 231.5km/h (125kt)
Ceiling	6.1km (20,000ft)
Operating Radius	204km (110nm)
RQ-8A Endurance	Over six hours
MQ-8B Endurance with Baseline 90kg Payload	Over eight hours
MQ-8B Endurance with 226kg (500lb Payload)	Over five hours

The characteristics of interest to this study are the operating radius and the endurance. The operating radius and the endurance allow the VTUAV to fly far away from the mother ship for sufficiently prolonged periods of time for the mission outlined in this study.

The VTUAV’s expected detection range depends on many factors, such as the following:

- weather conditions
- size and stealth of the enemy
- technical characteristics of the sensor
- Human performance

Thus, the expected detection range of a certain target cannot be determined as a fixed value. In this study, the detection range is set as a numerical factor with a wide range in order that the scenario can address all of the factors listed above.

2. Enemy Characteristics

The enemy vessel under consideration in this study is a FPB (Hellenic Navy). A FPB is a medium size ship of about 60 meters in length. The ship's greatest asset is its speed, which can easily reach 36 knots. The FPB is usually equipped with SSMs for long distance targets and guns for anti-air warfare or a close surface encounter. The picture below shows the Hellenic Ship SIMITZOPOULOS P-28. This model carries six SSMs with a maximum range of 27 Km, two OTO-MELARA 76mm/62 guns with a maximum range for surface targets of 16 Km, and two torpedoes for surface targets with a maximum range of 15 nm. One of its main detection devices is the navigational radar, which can detect low altitude flying objects like VTUAVs.

Figure 4. HS SIMITZOPOULOS (P-28)

D. SEARCH PATTERNS

When search operations are conducted in open sea, the most common and known search patterns originate from Search and Rescue (SAR) manuals. There are several basic search patterns detailed in SAR manuals, discussed in the following sections (after Lance, Carl, and Hill, 2003).

1. Parallel Search Pattern

The parallel search is commonly employed when the object of interest is likely to be anywhere in the search area. Figure 5 illustrates how the searcher's sensor range affects the pattern. A large sweep width results in less leg jumps and less ToT.

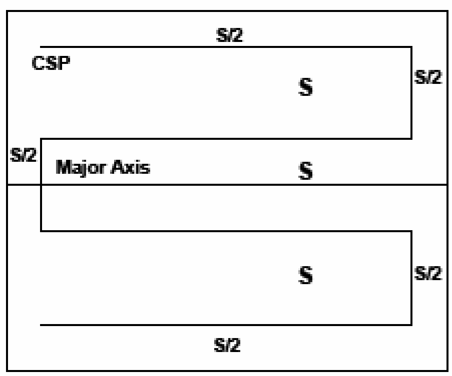

Figure 5. The parallel search pattern

2. Square Search Pattern

The square search is used when a possible initial position of the object of interest is available (DATUM) and a uniform coverage is preferable. Figure 6 shows this pattern type.

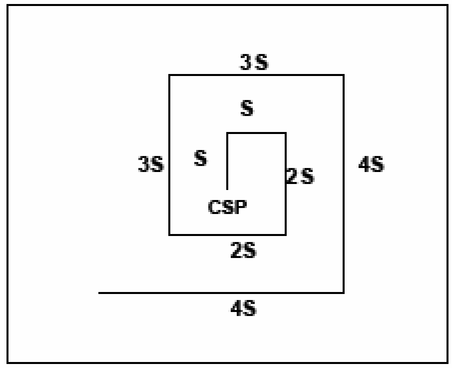

Figure 6. The square search pattern

3. Creeping Line Search Pattern

This pattern is similar to the parallel search, but yields better results if there is a chance that the object of interest will be at one end of the area rather than the other.

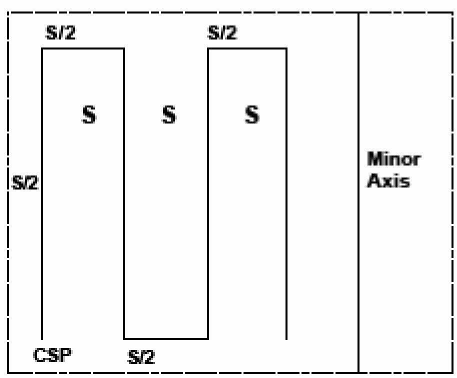

Figure 7. The creeping line search pattern

4. Sector Search Pattern

Forces will employ the Sector search pattern in situations when a DATUM is known and the object of interest is difficult to detect. The searcher passes many times from that last contact or initial position, thus increasing the probability of detection.

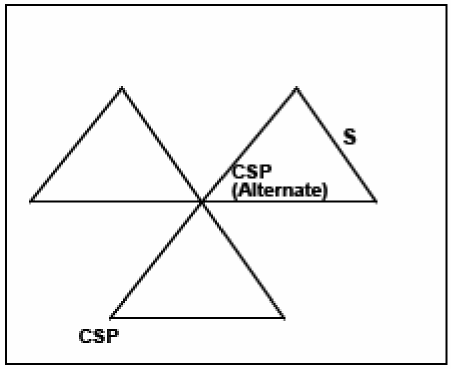

Figure 8. The sector search pattern

5. Barrier Patrol Search Pattern

This pattern is used when the object of interest moves evasively and at relatively high speeds within the area. The pattern proves ideal when the search area involves narrow passages or rivers.

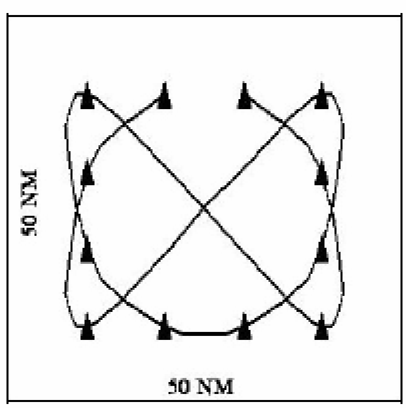

Figure 9. The barrier patrol search pattern

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II. SCENARIO APPROACH

A. DISCUSSION

One of the main research goals of this study is to gain insights into effective search patterns for the VTUAV. This problem is difficult to analyze, however, as it involves a large number of possible factors and a wide range of levels. Therefore, it is necessary to first investigate which of these factors are significant and then proceed to a more detailed exploration of the problem. This study distinguishes the relative importance of factors by executing a screening experiment with all of these factors. The screening experiment involves only one search pattern. After the screening experiment, a focused, comparison experiment is conducted with different search patterns in order to explore their contribution to the problem.

B. ABOUT THE SEARCH PATTERNS

The search patterns discussed in the previous section are broadly used in open seas, and each proves quite effective depending on the search problem specifications. However, the search area examined in this study is not an open sea, but is instead filled with islands and hiding positions. This fact would drive a Naval Commander to explore different ways to approach this situation. Common search patterns may not fully apply to this search operation because, for some cases, their design may prove to be unrealistic.

For example, a Naval Commander might order a search operation that would cover all possible hiding positions, leaving no island unchecked. Figure 10 displays an unrealistic approach using the parallel search pattern. If the Naval Commander applies this pattern, the enemy may remain undetected.

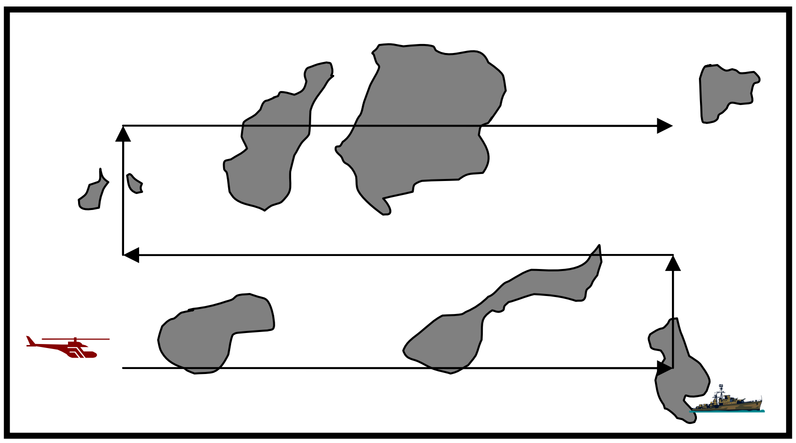

Figure 10. An unrealistic scenario. The enemy remains undetected.

In a slightly different situation, when the search area is large and the VTUAV's expected detection range is small (3-4 nm) due to bad weather conditions, a typical search pattern could demand an unrealistically large ToT. Figure 11 demonstrates such an example with the parallel search pattern. Given an area of 80×60 nm and a VTUAV speed of 120 knots, one area scan would require approximately 8-9 hrs. If one adds transit time, then the VTUAV's flight time would exceed its specifications.

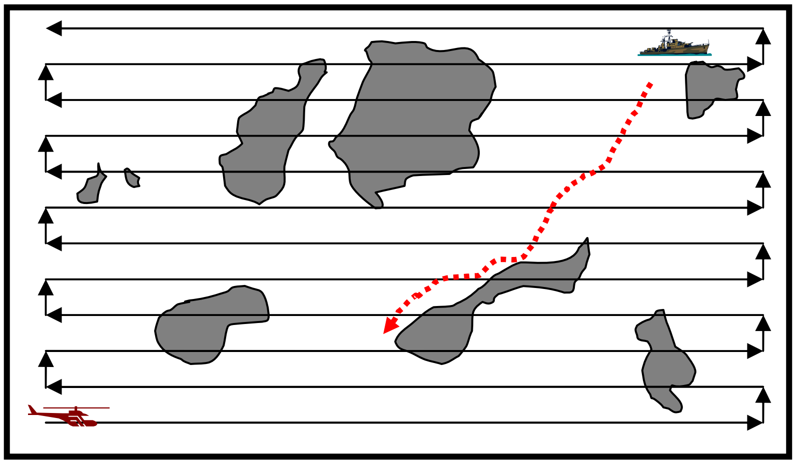

Figure 11. An unrealistic scenario. The ToT exceeds the VTUAV's specifications.

The search patterns used in this study originate from known open sea search patterns, but are modified according to the area geography. Some assumptions are made:

- The Naval Commander will attempt to investigate the islands closest to the naval force first, so every search pattern will start from the southern (lower) part of the map in MANA.
- All the islands will be searched.
- The VTUAV will fly close to the shorelines, even though its sensors possess good specifications. This study makes this assumption because the Naval Commander does not know the enemy's stealth capability or what kind of hiding positions the islands offer to the enemy.

This study employs three search patterns based on the assumptions above. The first pattern (Figure 12) originates from the parallel search and is called "parallel-modified."

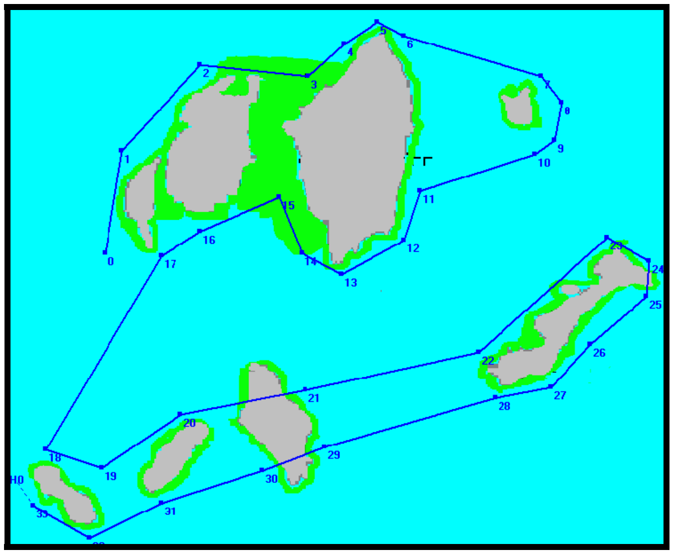

Figure 12.   The “parallel-modified” search pattern

The second pattern (Figure 13) is inspired from the square pattern and is called “spiral.”

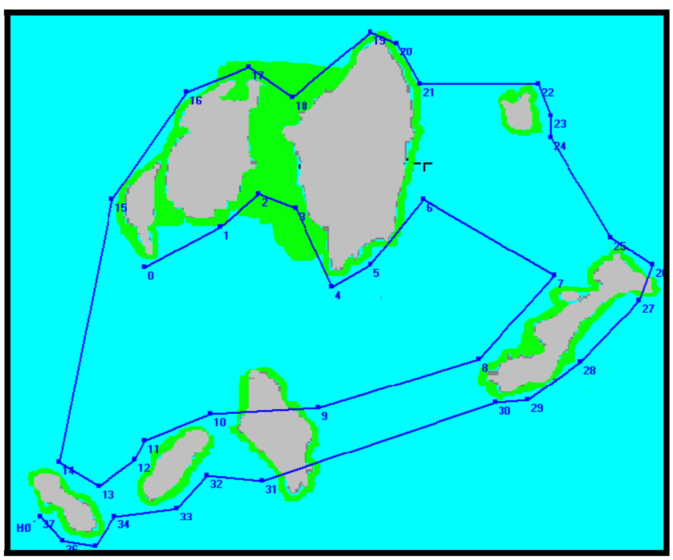

Figure 13.   The “spiral” search pattern

The last pattern (Figure 14) divides the search area into sectors and is called “sector-modified.”

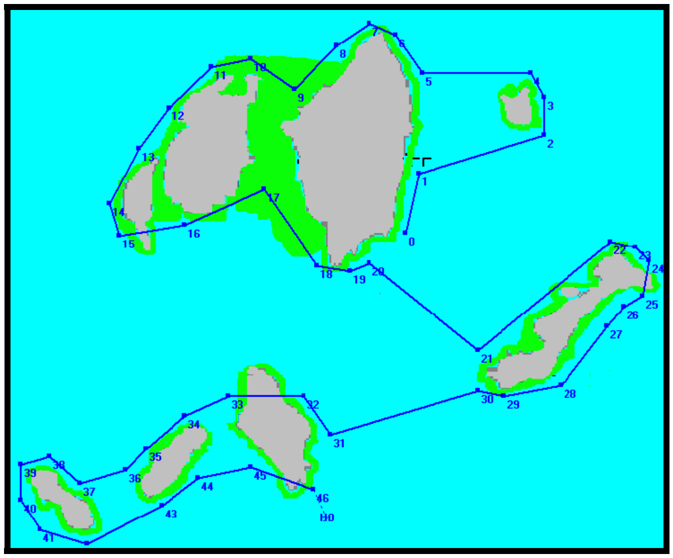

Figure 14. The “sector-modified” search pattern

There are several reasons that this problem does not use modifications of the creeping line or the barrier patrol pattern. The creeping line is very similar to the parallel search but does not entail search initiation at the islands closest to the naval force. The barrier patrol pattern is designed primarily for evasive targets and does not effectively accommodate this particular problem.

C. ABOUT THE SEARCH AREA

1. Area Size

The area size is an important factor in this study. Obviously, area size beyond the VTUAV’s specifications would pose problems to the mission. In this study, there are two area sizes used—40×40 nm and 80×80 nm.

2. Number of Islands

Another factor under consideration is the number of islands that exist in the area of interest. Few islands might present fewer hiding options for the enemy, and many islands might present more. The background terrain used in MANA is a modified section of the Cyclades Islands in Greece. This section includes the islands of Paros, Antiparos, Naxos, Donoussa, Folegandros, Sikinos, Ios, and Amorgos. The study employs two versions (see Figure 15) of this background. The first version includes four islands and is called “few islands,” and the second version includes all of the islands and is called “many islands.”

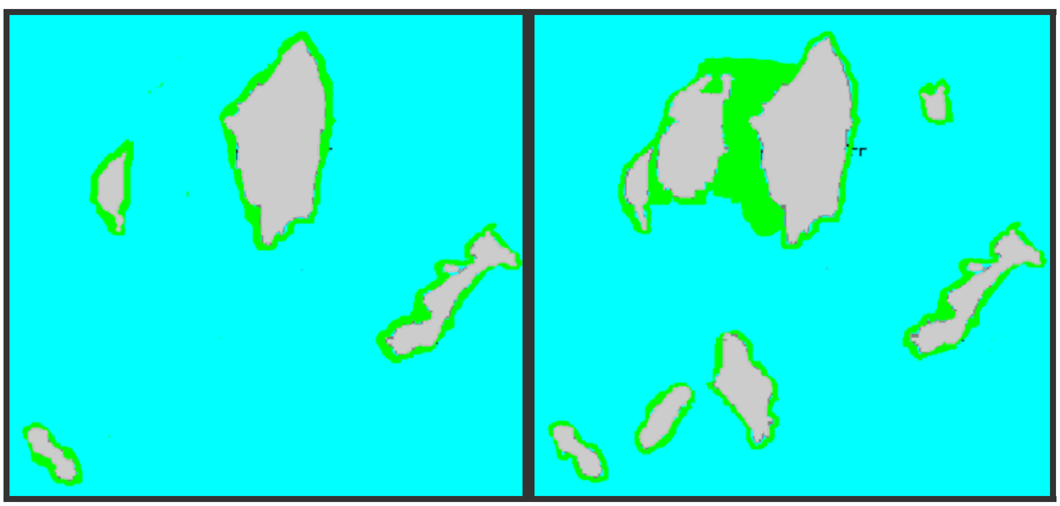

Figure 15. “few” and “many” islands

D. TIME-ON-TASK

Time-On-Task (ToT) is critical in a search and detection problem. While a VTUAV could easily fly for an 8-hour period, flight time may be truncated considering additional transit time to and from the area of interest. A more realistic ToT varies in the scenario from 1 to 6 hours.

E. ABOUT THE VTUAV

1. Movement and Speed

The VTUAV's movement is manipulated using the 51 personality attributes in MANA. This study explores the following attributes after extensive, interactive experimentation with the software.

a. "Next Waypoint" Attribute

This attribute denotes the determination or desire of the VTUAV's user to reach the next waypoint in the search pattern. Combined with the "Towards Enemy," this attribute can affect the outcome of the search. It is an integer quantity (50-100) in the "Personality" page. A higher number indicates a greater desire.

b. Speed

The VTUAV's speed varies between 60 and 120 knots. This range was scaled in MANA according to the area size and the battlefield grid squares in the software.

2. Sensors and Target Processing Capability

a. Expected Detection Range

The VTUAV's expected detection range is also a critical component. The sensor performs as a "cookie cutter," meaning that the probability of detection is equal to 1 within the sensor's range. While this may seem unrealistic, the capability is convenient since the expected detection range is serving more than one purpose. Sensor range in the experiments varies from 2-18 nm. This variation allows for differences arising from operation at night or during the day, in good or bad weather conditions, and using IR or visual cameras. In a situation in which the expected detection range is equal to 4 nm for a particular scenario run, this can mean that the operation is executed during the night with an IR sensor or during the day with low visibility and only a visual sensor. In our implementation in MANA, the sensor range is placed in the "Weapon" page as a "Weapon Range" input because every detection is represented as a "kill" for visual and practical purposes.

b. Target Processing Capability

Target processing capability denotes the speed at which the target identification procedure occurs. If this procedure is slow, then some contacts may be missed. Combined with a high VTUAV speed, slow processing may result in low performance. A realistic rate can be between 1 to 10 targets every 10 minutes. This rate is scaled and placed in the "Weapon" page as a "Max Targets/Step" input.

3. Stealth

The VTUAV's stealth can play an important role in the problem. For instance, low stealth may grant early warning to the enemy. This attribute is called "Personal concealment" and is a percentage quantity (0-75%).

F. ABOUT THE ENEMY

1. Movement and Speed

The FPB's movement is manipulated using the 51 personality attributes in MANA. This study explores the following attributes after extensive, interactive experimentation with the software.

a. "Next Waypoint" Attribute

This attribute denotes the determination or desire of the FPB's Commanding Officer to reach the objective, which is a hiding position near an island. The attribute is associated with a stepwise movement; the Commanding Officer does not sail directly to the island of his objective, but instead spends some time near islands in the FPB's path. This action can increase or decrease the enemy's survivability. This is an integer quantity (50-100).

b. "Cover" Attribute

This attribute designates the tendency of the FPB to take cover wherever available as it proceeds on its path. If a shoreline is close enough, the enemy veers off its course to take advantage of the extra coverage. This attribute is expressed as an integer quantity (0-100).

c. Speed

The FPB's speed is between 0 and 36 knots. This range is scaled in MANA according to the area size and the battlefield grid squares in the software.

2. Sensors

The FPB's expected detection range can also play a critical role in the problem. Like the VTUAV's expected detection range, it is represented by a "cookie cutter" within a range of 2 to 18 nm.

3. Stealth

A high level of stealth can allow the FPB to remain undetected. This attribute is called "Personal concealment" and is a percentage quantity (0-75%).

4. Communication

In MANA, the enemy is represented as multiple, identical squads of agents with different objectives (this paper will present more on this topic in a later section). Multiple enemy units situated in the area of interest may communicate with one another. If, for example, an agent detects the VTUAV, then it may instantly send a message to all other agents in the area. These agents can now take measures to avoid the VTUAV by changing course or remaining under cover until the VTUAV leaves their vicinity. MANA achieves this behavior by enabling the "Squad SA" and "Inorganic SA" pages, and by setting the "Away From Enemy" attribute to a value of -30. That is, alerted FPBs will desire to move away from the VTUAV and towards their next waypoint (and possibly cover).

G. SUMMARY

As detailed above, there are 15 possible factors considered in this study's scenario. Table 2 presents a summary of these factors and their types.

Table 2. Summary of factors for the screening

	FACTOR NAME	TYPE	LEVELS
1	Search Pattern	categorical	parallel-mod.
2	Area size	categorical	small-large
3	Number of islands	categorical	few-many
4	Enemy's communications	categorical	on-off
5	Time-on-Task	numeric	1-6 hrs
6	VTUAV's detection range	numeric	2-18 nm
7	VTUAV's speed	numeric	60-120 kts
8	VTUAV's "next waypoint"	numeric	50-100
9	VTUAV's target process	numeric	6-60 tar./hr
10	VTUAV's stealth	numeric	0-75 %
11	Enemy's detection range	numeric	2-18 nm
12	Enemy's speed	numeric	0-36 kts
13	Enemy's stealth	numeric	0-75 %
14	Enemy's "next waypoint"	numeric	50-100
15	Enemy's "cover"	numeric	0-100

Considering these factors, this study takes two steps:

- A screening experiment with 15 factors and the analysis.
- A comparison experiment comparing different search patterns and the analysis.

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III. METHODOLOGY AND ANALYSIS

A. SCREENING EXPERIMENT

1. MANA Scenarios and JMP

In order to run the MANA scenarios as effectively and fast as possible, factor levels have to be scaled. For convenience, the factor names are also altered for JMP. The following table shows the basic alterations made in MANA and in JMP.

Table 3. Appearance and scaling of factors in the software

AS THEY APPEAR IN THIS STUDY		**AS THEY APPEAR IN SOFTWARE**	
FACTOR NAME	**LEVELS**	**FACTOR NAME IN JMP**	**LEVELS IN MANA**
Area size	small-large	AreaSize	small-large
Number of islands	few-many	Islands	few-many
Enemy's communication	on-off	Ecomms	on-off
Time-on-Task	1-6 hrs	ToT	in timesteps*
VTUAV's detection range	2-18 nm	Usensor	10-80, 5-40*
VTUAV's speed	60-120 kts	Uspeed	50-100
VTUAV's "next waypoint"	50-100	Unextwp	50-100
VTUAV's target process	6-60 tar./hr	Uprocess	100-2000*
VTUAV's stealth	0-75 %	Ustealth	0-75
Enemy's sensor range	2-18 nm	Esensor	10-80, 5-40*
Enemy's speed	0-36 kts	Espeed	0-30
Enemy's stealth	0-75 %	Estealth	0-75
Enemy's "next waypoint"	50-100	Enextwp	50-100
Enemy's "cover"	0-100	Ecover	0-100

***Depending on the area size.**

One of the most important issues for a scenario run in MANA concerns how one represents the random nature of the enemy’s movement. When the VTUAV initiates its search, the Naval Commander does not know the enemy’s current position or intended destination. This study assumes that the enemy is already positioned in the area of interest and is likely heading to a hiding position near an island. To assign a certain and fixed path of enemy movement would be to compromise the integrity of this study by eliminating the desired random movement. One method of circumventing this problem involves the creation of multiple enemy squads with identical personalities, but different hiding positions. An enemy squad of 10 agents is randomly distributed in the area of interest and is assigned to go to a certain island to hide. So, for the “many islands” area (8 islands), there are 10×8=80 agents. For the “few islands” area (4 islands), squads formerly assigned to now non-existent islands (from the “many islands” scenario) are assigned to go to one of the remaining islands. Therefore, the total number of FPB agents is, again, 80. These 80 agents together represent one enemy and not 80 enemies. The greater number, however, creates the element of movement, possible starting positions, and intended randomness in the scenarios. Replication of these scenarios many times ensures a greater degree of realistic unpredictability across the entirety of the experiment.

Another issue in MANA concerns natural agent movement and behavior. Table 4 outlines the basic settings used in this study. See the MANA manual for precise definitions of these factors.

Table 4. Fixed values for agent movement in MANA

FIELD OR PAGE	ATTRIBUTE NAME	VTUAV SETTING	ENEMY SETTING
BATTLEFIELD	AGGREGATION RADIUS	5 (2.5)	5 (2.5)
PERSONALITY	ENEMIES	0	-100
PERSONALITY	IDEAL ENEMY	50	0
PERSONALITY	LINE CENTRE	75	100
PERSONALITY	ENEMY THREAT	50	-30
ALGORITHM	ALGORITHM	PATH	STEPHEN
ALGORITHM	MOVE PRECISION	10	0

2. MANA Assumptions

MANA operates under certain assumptions that affect other aspects of the study. First, MANA assumes that change in VTUAV altitude does not have any impact to its sensor range. This limitation is built into the software and cannot not be altered. Therefore, the VTUAV's altitude is set to 300 meters.

Another limitation is that the Traveling Salesman Problem property (TSP) cannot be utilized, as it does not result in realistic movements for the VTUAV. This disadvantage results from the presence of the 80 agents in the simulation. Apparently, this large number of agents causes the VTUAV to veer off its course in an unnatural way so that it can address all the agents. To enhance a natural movement in a local level, the "movement precision" of the VTUAV is set to 10 and the "Ideal Enemy" personality attribute is set to 50.

Finally, our implementation in MANA assumes that detection and identification of the target occur at the same time. This is not likely to take place in real situations. In reality, the searcher first spots an unidentified target and then proceeds to identify it. If the weather conditions are fair and the target size is large enough, then the time for the target identification can be minimal. In many cases, however, the searcher must approach the target and take a better look. The TSP function would simulate this type of movement and behavior, but cannot be used because of the reasons already mentioned.

Lastly, some remarks about the “enemy communication” modeling in MANA are in order. Although this categorical factor, when enabled to “on,” simulated the presence of more than one unit in the area, the movement of agents in some cases looked unnatural. While this study included this function in experimentation, there are some reservations about the quality of this factor in terms of modeling.

3. Design of Experiment (DOE)

The factors mentioned in the last section are both numeric and categorical, as demonstrated below. One should exercise great care when handling a mix of numeric and categorical variables. It is better to handle the categorical variables as possible problem states and replicate the DOE for the numeric variables within these states. This amount of caution demands more effort, but it also produces a more reliable outcome. This experiment establishes 8 states, again demonstrated below.

- “Small” area, “few” islands, enemy communication “ON”
- “Small” area, “few” islands, enemy communication “OFF”

- “Small” area, “many” islands, enemy communication “ON”
- “Small” area, “many” islands, enemy communication “OFF”
- “Large” area, “few” islands, enemy communication “ON”
- “Large” area, “few” islands, enemy communication “OFF”
- “Large” area, “many” islands, enemy communication “ON”
- “Large” area, “many” islands, enemy communication “OFF”

The quantity of the 11 numerical factors and their levels used in the screening experiment do not allow for the creation of a full factorial design of experiment, which would explore every possible combination. In order to minimize the time and effort needed to execute a simulation that big, the Nearly Orthogonal Latin Hypercube (NOLH) design has been chosen (Sanchez, 2005). This design is a “space filling design” which uses a well-chosen subset of all possible scenario combinations (Sanchez, and Lucas, 2002). The NOLH selects only 33 runs (for the 11 numerical variable case) in such a way that the outcome will sample effectively from the possible design points. The scatter plot in Figure 16 shows the space filling property. The correlation matrix in Figure 17 proves that the 33 runs, which are selected by the DOE, are barely correlated, indicating a near orthogonality between the input factors (Kleijnen, Sanchez, Lucas, and Cioppa, 2005).

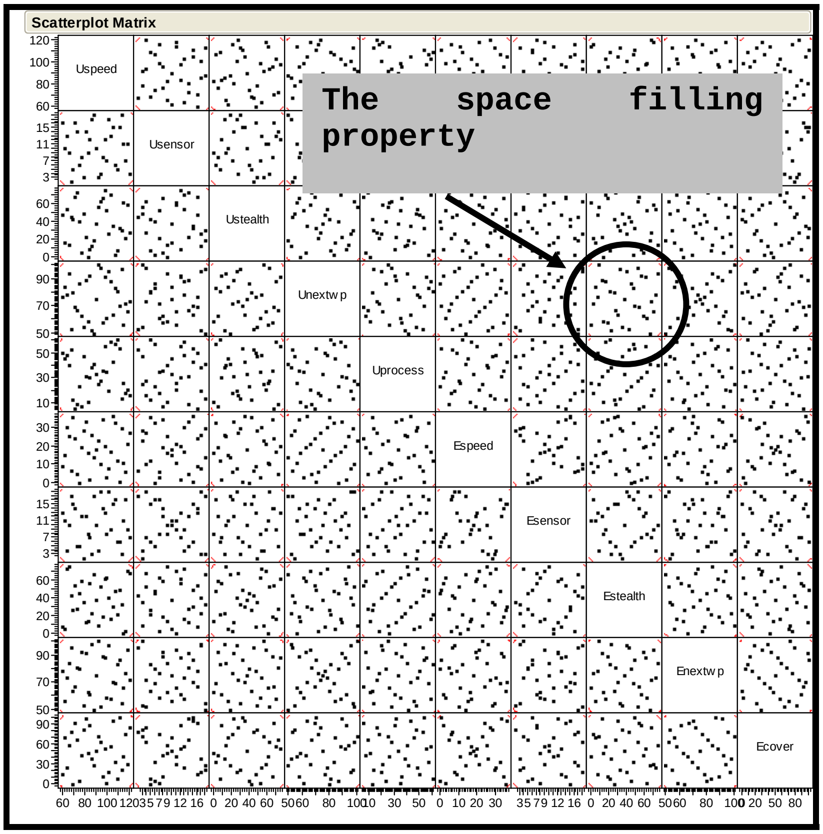


Figure 16. Scatterplot matrix for the screening experiment

	TOT	Uspeed	Usensor	Ustealth	Unextwp	Uprocess	Espeed	Esensor	Estealth	Enextwp	Ecover
TOT	1										
Uspeed	-0.00734	1									
Usensor	0.001181	-0.00267	1								
Ustealth	0.001869	-0.00213	0.000818	1							
Unextwp	-0.0099	0.010414	-0.02108	-0.00288	1						
Uprocess	0.002281	0.000205	-0.02935	-0.00501	0.011801	1					
Espeed	0.026008	-0.00635	0.010358	-0.015	0.004167	0.003145	1				
Esensor	-0.00182	-0.0016	8.08E-05	0.000818	-0.01637	0.013344	0.00681	1			
Estealth	0.011813	-0.01193	0.005079	0.014421	0.01902	0.001052	0.007179	-0.00344	1		
Enextwp	-0.0022	0.010758	-0.01252	-0.00351	0.019108	-0.01117	0.009674	-0.0198	-0.02577	1	
Ecover	0.005957	0.017857	0.005017	-0.00205	0.015208	0.001072	0.017025	-0.00266	-0.02924	0.009452	1

Figure 17. Correlation matrix for the screening experiment

In summary, the screening experiment consists of 33×8=264 runs. Replicating 50 times each, this yields 13,200 simulated searches.

4. Measure of Effectiveness (MOE)

The effectiveness of the screening experiment is measured according to the number of enemy detections that occur. Since the number of enemy agents is 80, the proportion of the number of agents detected divided by 80 is the empirical probability of enemy detection in the area. The Naval Commander wants to maximize this probability.

B. SCREENING EXPERIMENT ANALYSIS

1. Model

The final model explains 88% of the observed variation. The actual by predicted values plot (Figure 18) indicates that the model seems to be adequate and can yield reasonable results.

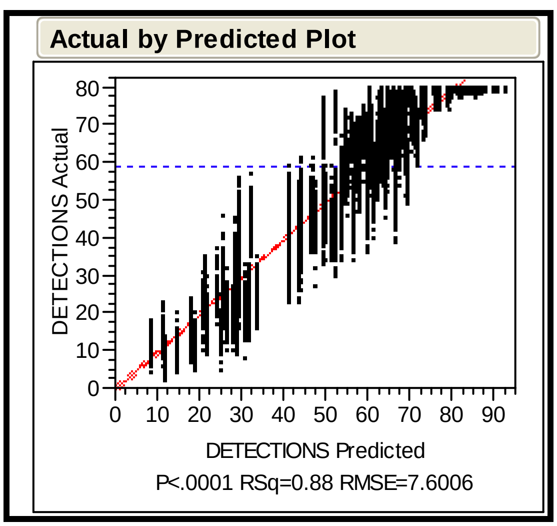


Figure 18. Actual by predicted plot

The plots below demonstrate that, from the three categorical factors, the area size and the "enemy communication" have an impact on the problem, while the number of islands does not play a significant role. These plots show if the difference of the observed means by category are statistically different. Identical letters indicate no difference, while different letters indicate that the means are different. It is important to be clear about the analyst's responsibility in this aspect of the experiment. Two means may be statistically different, but if this difference is relatively small, the analyst may decide that the difference is of no practical consequence, depending on his expertise in the subject.

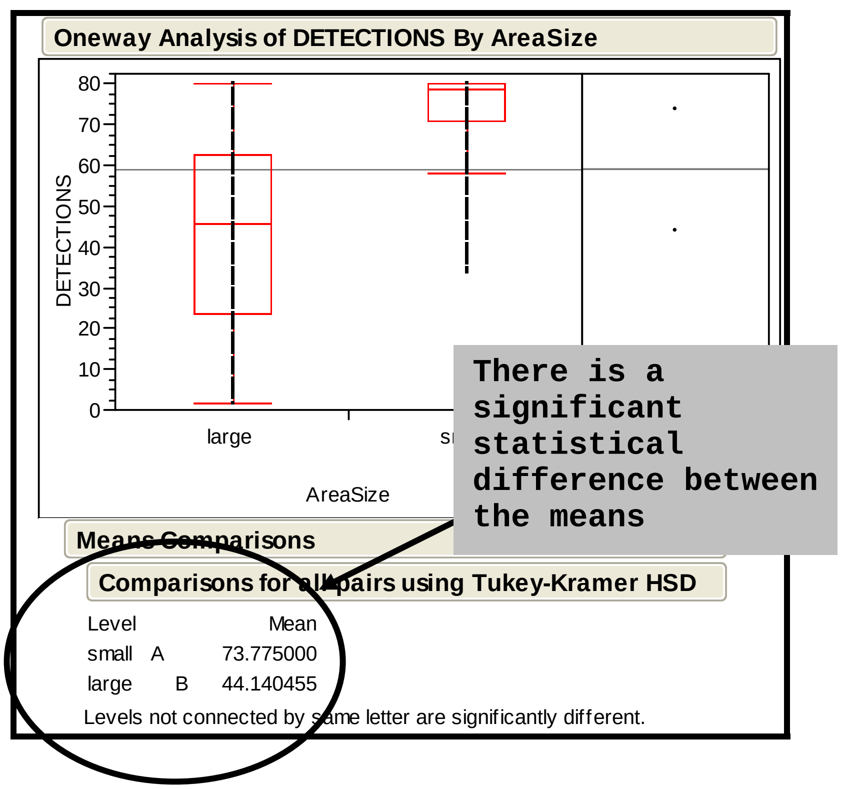


Figure 19. Number of detections by area size

Variability in the number of islands may be a relatively insignificant factor as a result of the assumption that the VTUAV will fly over all the islands. In other words, the length of the shorelines affects only the flying time and not the probability of detection.

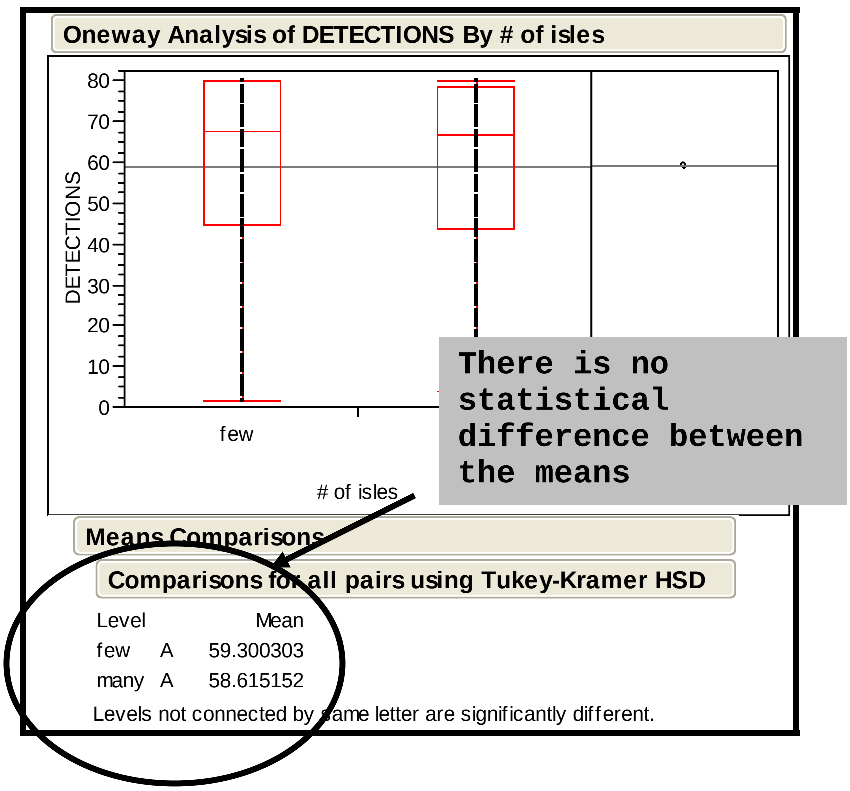


Figure 20. Number of detections by number of islands

If "enemy communication" is "on," the number of detections slightly decreases. This decrease is only around 4%. Nevertheless, the study incorporates this factor in the model and in the comparison experiment because, as was previously discussed, the factor is poorly modeled, and the effect may be more significant than it appears to be. The factor's impact takes into account the fact that a possible coordinated enemy operation with more than one unit increases its survivability. These units need not be warships; fishing vessels or troops on some islands can function as valuable lookouts. If the FPB knows the current position of the VTUAV, then it can outmaneuver it. As the small difference in percentage reveals that the odds are with the VTUAV, the enemy should rely on tactics and intelligence to improve its chances.

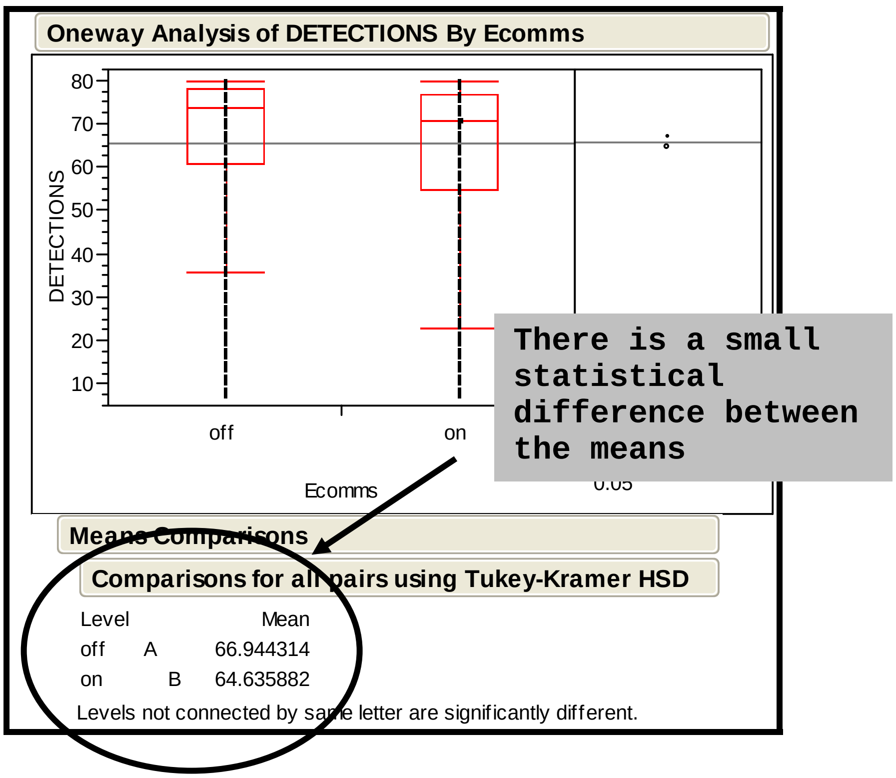
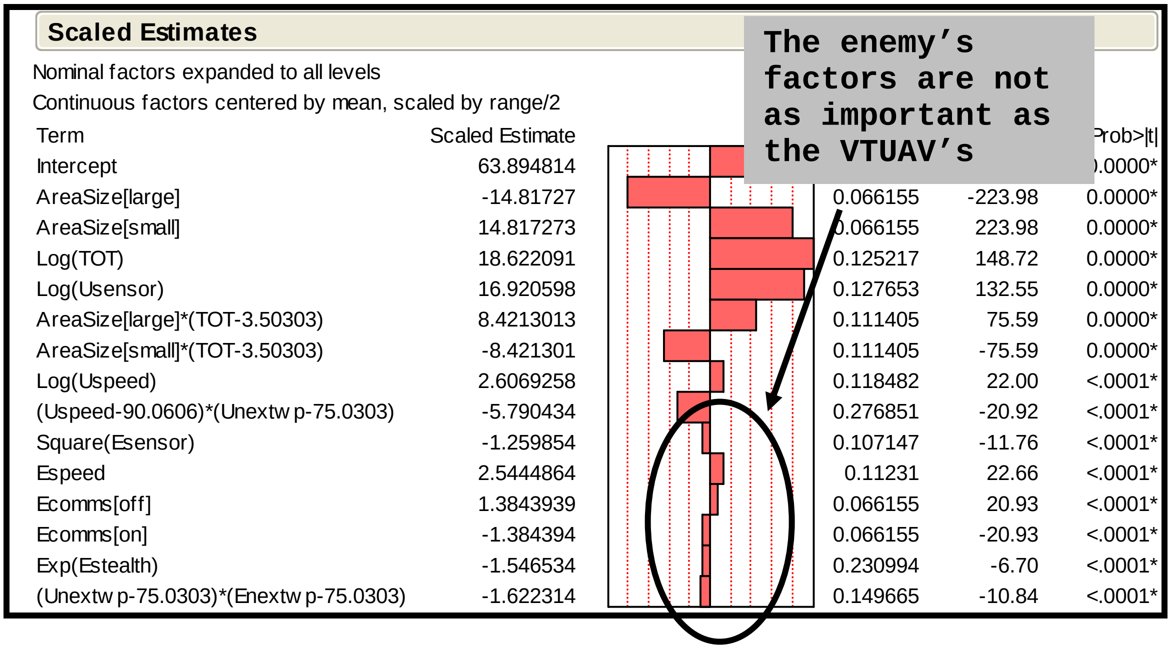


Figure 21. Number of detections by “enemy communication”

The following graph (Figure 22) is the scaled estimates graph. This powerful tool visually represents the degrees in which the selected factors and interactions contribute to the problem (Sanchez, and Lucas, 2002). The graph clearly expresses that factors associated with the enemy’s behavior have a smaller impact relative to those that explain the VTUAV’s behavior.



Scaled Estimates

Nominal factors expanded to all levels

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate				Prob>|t|
Intercept	63.894814				.0000*
AreaSize[large]	-14.81727		0.066155	-223.98	0.0000*
AreaSize[small]	14.817273		0.066155	223.98	0.0000*
Log(TOT)	18.622091		0.125217	148.72	0.0000*
Log(Usensor)	16.920598		0.127653	132.55	0.0000*
AreaSize[large]*(TOT-3.50303)	8.4213013		0.111405	75.59	0.0000*
AreaSize[small]*(TOT-3.50303)	-8.421301		0.111405	-75.59	0.0000*
Log(Uspeed)	2.6069258		0.118482	22.00	<.0001*
(Uspeed-90.0606)*(Unextw p-75.0303)	-5.790434		0.276851	-20.92	<.0001*
Square(Esensor)	-1.259854		0.107147	-11.76	<.0001*
Espeed	2.5444864		0.11231	22.66	<.0001*
Ecomms[off]	1.3843939		0.066155	20.93	<.0001*
Ecomms[on]	-1.384394		0.066155	-20.93	<.0001*
Exp(Estealth)	-1.546534		0.230994	-6.70	<.0001*
(Unextw p-75.0303)*(Enextw p-75.0303)	-1.622314		0.149665	-10.84	<.0001*

Figure 22. Scaled estimates for the screening experiment

Figure 23 depicts the prediction formula, which can be used to create a tool for decision making.

Prediction Expression

-33.576060850369

+Match(AreaSize) { "large" ⇒ -14.8172727272273; "small" ⇒ 14.8172727272725; else ⇒ . }

+20.7863739658617*Log(TOT)

+15.4017917787391*Log(Usensor)

+Match(AreaSize) { "large" ⇒ (TOT-3.50303030303035)*3.3685205284804; "small" ⇒ (TOT-3.50303030303035)*-3.3685205284804; else ⇒ . }

+7.52199787615012*Log(Uspeed)

+(Uspeed-90.0606060606061)*(Unextw p-75.030303030303)*-0.0077205788393

+-0.0078740894321*Esensor^2

+0.14136035615943*Espeed

+Match(Ecomms) { "off" ⇒ 1.38439393939337; "on" ⇒ -1.3843939393934; else ⇒ . }

+-8.285203722e-33*Exp(Estealth)

+(Unextw p-75.030303030303)*(Enextw p-75.030303030303)*-0.002595702585

Figure 23. Prediction formula for the screening experiment

The plots in Figures 24 and 25 utilize this formula to help the Naval Commander maximize his search effort. Since the most important factors are the area size, the ToT, and VTUAV's expected detection range, the plots use these variables to predict the probability of detection while all the remaining factors are set to a reasonable value. For example, if the area of interest is 40×40 nm, the Naval Commander seeks a probability of detection greater than 0.9, and the expected detection range is 8 nm, then a ToT of at least 2.25 hours is required. The plots also show that when the area size is small, then there is no need to dedicate more than 3.5-4 hours in the area. The graph makes it clear that a ToT of 6 hours does not dramatically improve the probability of detection.

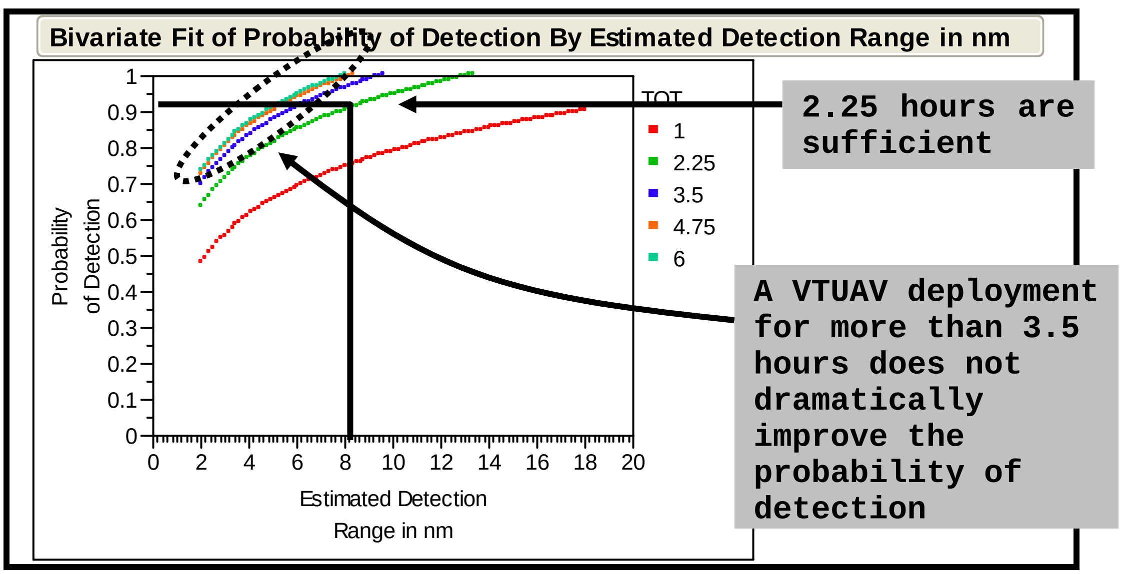


Figure 24. Decision-making plot for a 40×40 nm area (best viewed in color)

On the other hand, given a larger area of 80×80 nm and the same requirements, a ToT of more than 6 hours is necessary. This fact may force the Naval Commander to deploy a second VTUAV in the area.

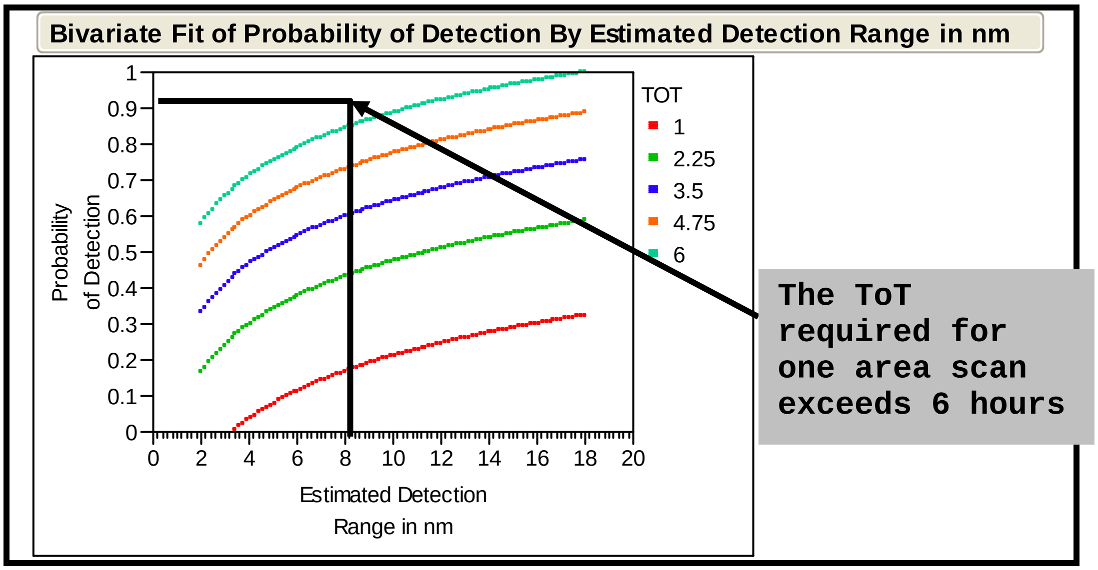


Figure 25. Decision-making plot for a 80×80 nm area (best viewed in color)

These graphs are applicable only to the specific problem in this study and not to situations in general. Approaches to situations will vary depending on geography, area size, and search pattern. Nevertheless, these graphs do demonstrate how easy is to make user-friendly tools for a decision maker. Such tools can provide quantitative indications to the Naval Commander of how many VTUAVs he should use and for how much time in order to maximize the probability of detection in any given situation. Note: these tools were obtained using the “parallel-modified” search pattern and fixed values in the formula, as listed below:

- VTUAV’s speed 100 kts
- VTUAV’s “next waypoint” 75
- Enemy’s communication “on”
- Enemy’s speed 18 kts
- Enemy’s stealth 37
- Enemy’s “next waypoint” 75
- Enemy’s expected detection range 10 nm

2. Findings

The screening experiment reveals highly interesting effects and interactions. While the most important factors are the area size, the ToT, and the VTUAV’s expected detection range, the study also considers several other factors whose importance is unexpectedly minimal.

For instance, the VTUAV’s target processing capability and stealth do not seem to hold much significance. The capability is most likely unimportant because the VTUAV’s detection range can diminish the importance of other VTUAV’s characteristics. If the expected detection range is sufficiently large, the target processing capability and the stealth do not matter any more.

Surprisingly, the number of islands is trivial as well. Apparently, it does not matter if the area contains few or many islands. This may be attributed to the assumption that the VTUAV will search all islands. If the VTUAV searches every island, then the greater shoreline length does not affect the number of detections.

The enemy’s “cover” attribute is ultimately not important either. This relative insignificance results from the tendency of the FPB to take cover wherever this cover is available on its path. A tendency to sail towards shorelines does not seem to provide any extra advantage to the enemy. This does not mean that the shorelines do not provide any coverage. It simply means that the enemy gains little by slightly altering its course in order to sail closer to the shoreline. If the VTUAV is in the vicinity, it will detect the enemy without problems.

The rest of the factors do not have as significant an impact as the area size, the ToT, or the VTUAV's expected detection range, but contribute in the search scenario as main effects or interactions. The discussion in the next section, along with Figures 26 and 27, explores all of the important factors and their significance in realistic situations.

a. Area Size

The Area size operates as a main factor in the scenario, but also loses its centrality to the situation as it interacts with the ToT. The number of enemy detections decreases when the area size increases; however, if the ToT is large enough, it will balance the potential losses.

b. Time-on-Task (ToT)

The ToT is a critical factor. It appears to participate in a non-linear fashion in the problem. In other words, slight increases in available ToT dramatically increase the probability of detection.

c. VTUAV's Expected Detection Range

Like ToT, the VTUAV's expected detection range appears to operate in a non-linear fashion. A larger range makes operations in larger areas possible, and increases dramatically the probability of detection

d. VTUAV’s Speed

The VTUAV’s speed is an important factor, but does not seem to contribute to the problem as much as the expected detection range does. Like the detection range, the speed factor participates as a main effect, but as the scaled estimates in Figure 22 show, speed is not critical to the VTUAV’s mission. The speed’s quadratic curve with its concave down structure suggests that the probability of detection does not drastically improve at maximum speeds. A moderate speed of 100 knots can be equally effective. This trend is readably understandable considering the fact that the enemy has a limited speed as well. Given a different type of target with a broader range of speed, the enemy could possibly outmaneuver the VTUAV and change the importance of the speed factor. Of course, when the size of the area in question is quite large, a high speed also proves useful in minimizing ToT.

e. VTUAV’s “next waypoint” Attribute

VTUAV’s “next waypoint” attribute interacts with the VTUAV’s speed in a counterproductive way. When speed increases and the determination of the VTUAV’s user to reach the next waypoint in the search pattern is high, the number of detections decreases. These factors denote hastiness, which results in poor search outcomes. Less determination to reach the next waypoint means more time spent searching along the way, and thus more detections.

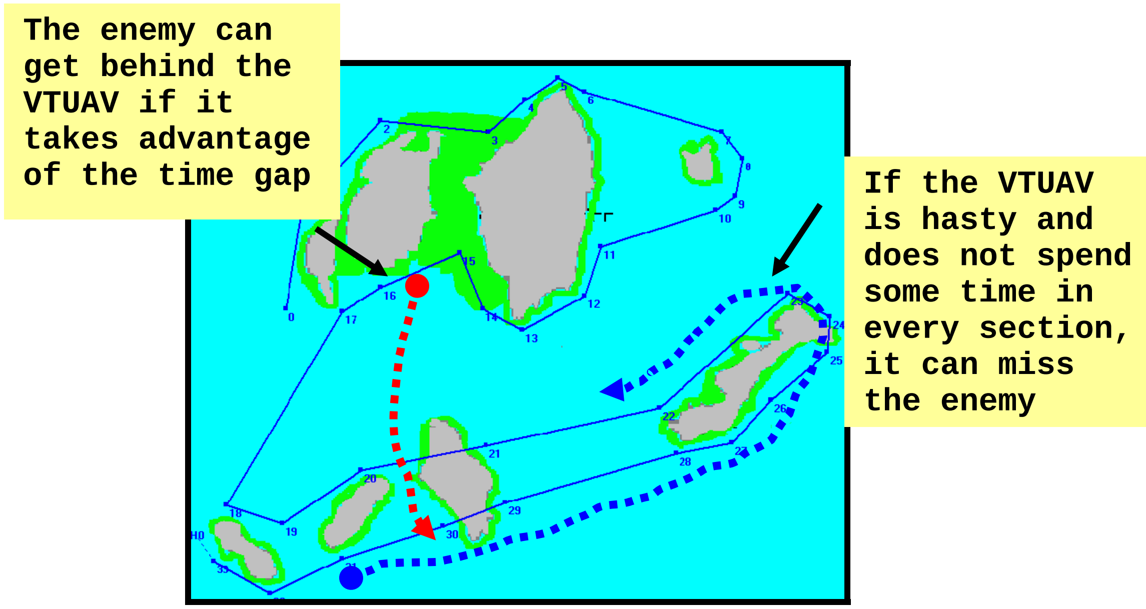


Figure 26. A visual interpretation of the "next waypoint" interaction

f. Enemy's Speed

Enemy speed is also a noteworthy factor, for although it does not contribute immensely to scenario outcomes, the effects of speed reveal interesting trends. If the enemy's speed increases, then the number of detections increases as well. Surprisingly, a low speed does not decrease the enemy's survivability. In contrast, a high speed allows the enemy to be near its hiding position earlier, which will inevitably result in detection as the VTUAV flies from island to island. A high enemy speed increases the possibility that the VTUAV and the enemy will meet at some point.

g. Enemy's "next waypoint" Attribute

This attribute interacts with the VTUAV's "next waypoint." When both enemy and VTUAV attributes are high, the number of detections is low. When both are low, the number of detections is low again. This phenomenon is understandable when one considers a situation in which the VTUAV passes from an island and the enemy arrives there after the VTUAV has gone. If the VTUAV user is hasty, then there is a greater possibility that the enemy will arrive after the VTUAV is gone. If the VTUAV user is spending more time in the sub area, and is not so eager to move to the next waypoint, then the enemy should delay its arrival in hopes that it will avoid the VTUAV. This interaction reveals that a “stepwise” movement tactic increases the enemy’s survivability. In other words, the enemy should not move directly to its objective, but make a step-by-step advance movement so that it will arrive after the VTUAV has already passed from there. Figure 26 provides a visual representation of this interaction.

h. Enemy’s Expected Detection Range

The enemy’s expected detection range contributes to the outcomes of the scenario in a secondary degree. If the enemy can detect the VTUAV at a relatively long distance, the probability of detections in the other direction decrease significantly. Medium and small detection ranges do not provide any serious advantage to the enemy.

i. Enemy’s Stealth

Enemy stealth is a minor factor to detection probability. Small or medium stealth capability does not provide any significant advantage to the enemy; high stealth allows for greater enemy survivability.

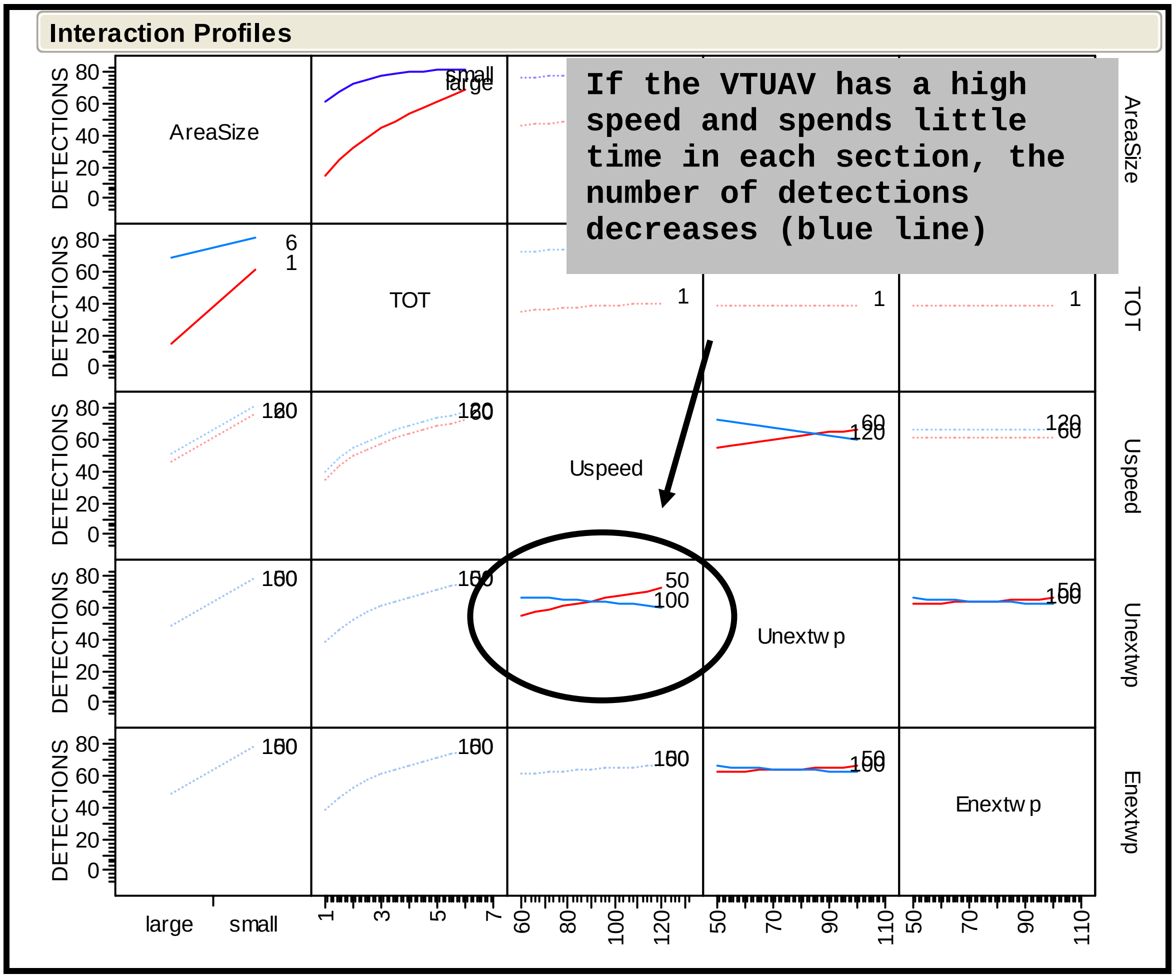


Figure 27. Interaction profiles for the screening experiment

3. Conclusions

a. For the VTUAV

The factors that ultimately determine the VTUAV's success of detecting the enemy are the area size, the ToT, and the expected detection range. Forces in search situations cannot control area size because it depends on the geography and nature of the operations. Conversely, these forces may control ToT and detection range beforehand by ensuring that VTUAVs have as much endurance and sensor range as possible.

b. For the Enemy

The enemy cannot guarantee avoidance of detection. If it is in the VTUAV's path, there will be no escape. Tactically, the enemy increases survivability by operating in coordinated groups and promoting a stepwise movement to its objective. In respect to equipment, the enemy can invest in stealth technology and better sensors. Realistically, however, better technology cannot secure survival unless it is top of the line.

C. COMPARISON EXPERIMENT

1. MANA Scenarios and JMP

The concept of the 80 randomly distributed enemy agents in the screening experiment remains in the comparison experiment. The levels of the numerical and categorical factors as well as any fixed values in MANA also remain the same. The comparison experiment involves the three search patterns previously discussed. In JMP, the main goal is not to form a model, but to compare different MOEs.

Table 5 provides a summary of the factors varied in the comparison experiment.

Table 5. Summary of factors in the comparison experiment

	FACTOR NAME	TYPE	NAME/RANGE
1	Search Pattern	categorical	parallel-mod.
			spiral
			sector-mod.
2	Area size	categorical	small-large
3	Enemy’s communications	categorical	on-off
4	VTUAV’s sensor range	numeric	2-18 nm
5	VTUAV’s speed	numeric	60-120 kts
6	VTUAV’s “next waypoint”	numeric	50-100
7	Enemy’s sensor range	numeric	2-18 nm
8	Enemy’s speed	numeric	0-36 kts
9	Enemy’s stealth	numeric	0-75 %
10	Enemy’s “next waypoint”	numeric	50-100

The comparison experiment does not use the ToT variable. This is necessary because each search pattern has different characteristics, and thus a fixed ToT value would result in misleading outcomes. ToT is measured and participates in a MOE described in a later section.

2. Design of Experiment (DOE)

For reasons detailed in the screening experiment, the categorical variables are treated as the following 12 states:

- “Parallel-modified,” “Small” area, enemy communication “ON”
- “Parallel-modified,” “Small” area, enemy communication “OFF”
- “Parallel-modified,” “Large” area, enemy communication “ON”
- “Parallel-modified,” “Large” area, enemy communication “OFF”
- “Spiral,” “Small” area, enemy communication “ON”
- “Spiral,” “Small” area, enemy communication “OFF”
- “Spiral,” “Large” area, enemy communication “ON”
- “Spiral,” “Large” area, enemy communication “OFF”

- “Sector-modified,” “Small” area, enemy communication “ON”
- “Sector-modified,” “Small” area, enemy communication “OFF”
- “Sector-modified,” “Large” area, enemy communication “ON”
- “Sector-modified,” “Large” area, enemy communication “OFF”

As there are seven important numerical values, this study uses the Orthogonal Latin Hypercube design (Sanchez, 2005). This design is a “space filling design” that uses a proportion of all the possible scenario combinations. It selects 17 runs in such a way to efficiently sample across the possibilities (Sanchez, and Lucas, 2002). The correlation matrix in Figure 28 proves that the 17 runs, which were selected by the design, are barely correlated, ensuring a near orthogonality between the input factors (Kleijnen, Sanchez, Lucas, and Cioppa, 2005). The scatter plot in Figure 29 shows the space filling property.

	Usensor	*Uspeed*	*Unextwp*	*Esensor*	*Espeed*	*Estealth*	*Enextwp*
Usensor	1						
Uspeed	0.002618	1					
Unextwp	-0.00234	0.004146	1				
Esensor	0	0.005889	0.005468	1			
Espeed	-0.00435	-0.01051	-0.00766	-0.00761	1		
Estealth	0.004179	0.001526	-0.00275	-0.00418	0.012725	1	
Enextwp	0.008592	-0.00607	-1.5E-05	-0.00625	-0.01216	-0.00675	1

Figure 28. Correlation matrix of the comparison experiment

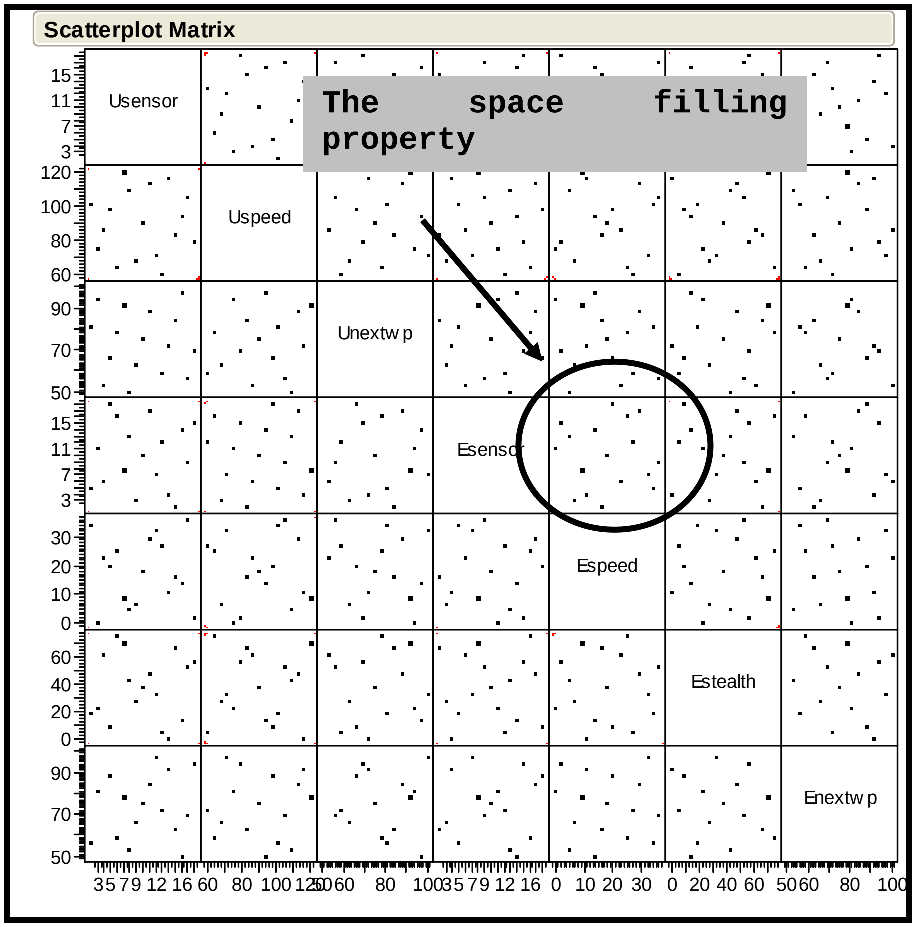


Figure 29. Scatter plot of the comparison experiment

In summary, the screening experiment consists of 17×12=204 runs. Replicating 50 times each, this yields 10,200 design points.

3. Measures of Effectiveness (MOE)

The comparison experiment considers three MOEs:

- The number of enemy detections
- The ratio of the number of enemy detections over the required ToT for each search pattern to be completed one time (i.e., one area "scan")
- The number of enemy detections for each enemy squad

The first MOE expresses any difference between search patterns, regardless of time. The second MOE essentially measures the rate of detections, and thus may evaluate the time-efficiency of each search pattern. The last MOE assesses any difference between the enemy squad detections and indicates possible effective enemy plans.

D. COMPARISON EXPERIMENT ANALYSIS

1. Findings

a. MOE "number of detections"

If ToT is not under consideration, then the three patterns are not different. The number of detections remains the same throughout each. Figures 30 and 31 compare the number of detections in each search pattern by area sizes. The same outcome results when the patterns are compared by different VTUAV expected detection ranges. Apparently, these results do not vary in day or night, or poor or good visibility.

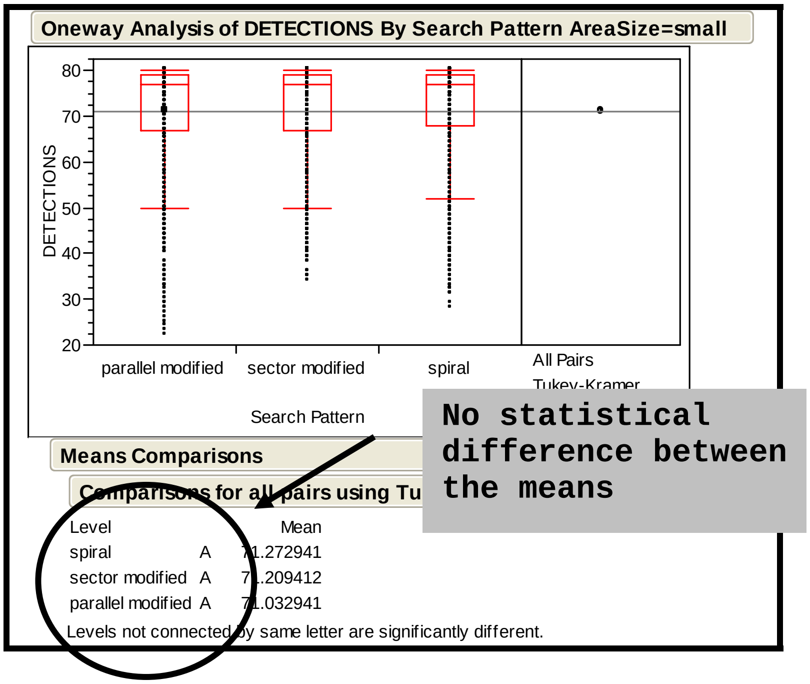


Figure 30. Comparison of detection means for a 40×40 nm area

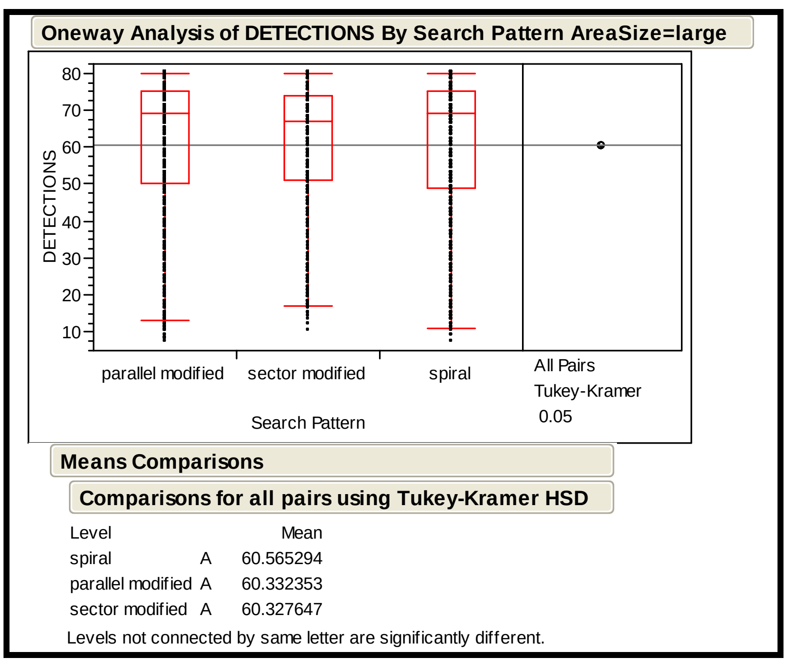


Figure 31. Comparison of detection means for a 80×80 nm area

b. MOE "rate of detections"

According to the MOE, the "sector-modified" pattern is the most time-efficient of the search patterns. Since the three patterns produce the same number of detections, the only criterion of choosing one over another is the rate of detection. The "sector-modified" search pattern is not necessarily the best pattern; it is merely the fastest one.

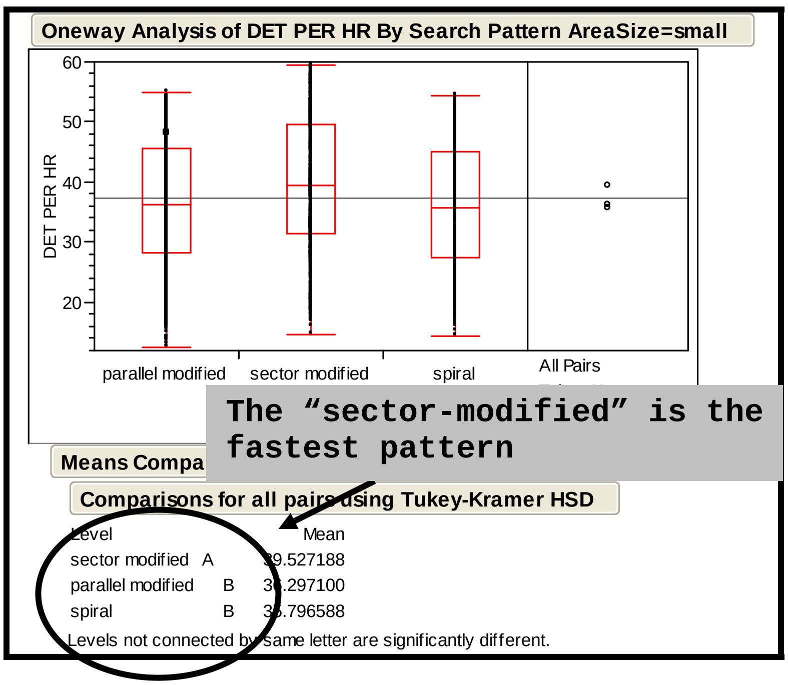


Figure 32. Comparison of detection rate means for a 40×40 nm area

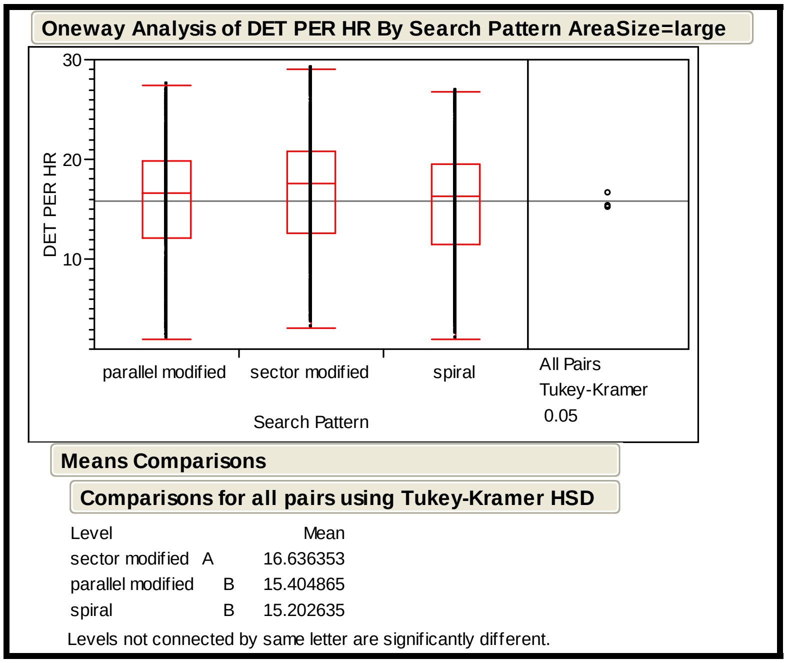


Figure 33. Comparison of detection rate means for a 80×80 nm area

c. MOE "squad detections"

This MOE explores possible tactics the enemy can use to avoid exposure. According to this research, enemy squads heading to islands the VTUAV searches first suffer a lower probability of detection. The difference in detection between the first and last islands searched reaches up to 12% (Figure 34). This reveals a possible enemy tactic: If the enemy wants to avoid detection, it should attempt to move behind the VTUAV and advance to the islands that the VTUAV searched first. This is a bold movement. The enemy wagers that the VTUAV will make just one run over all islands and then return to the naval force. If, in addition, the enemy is operating in coordination with other units, then its chances for survival increase.

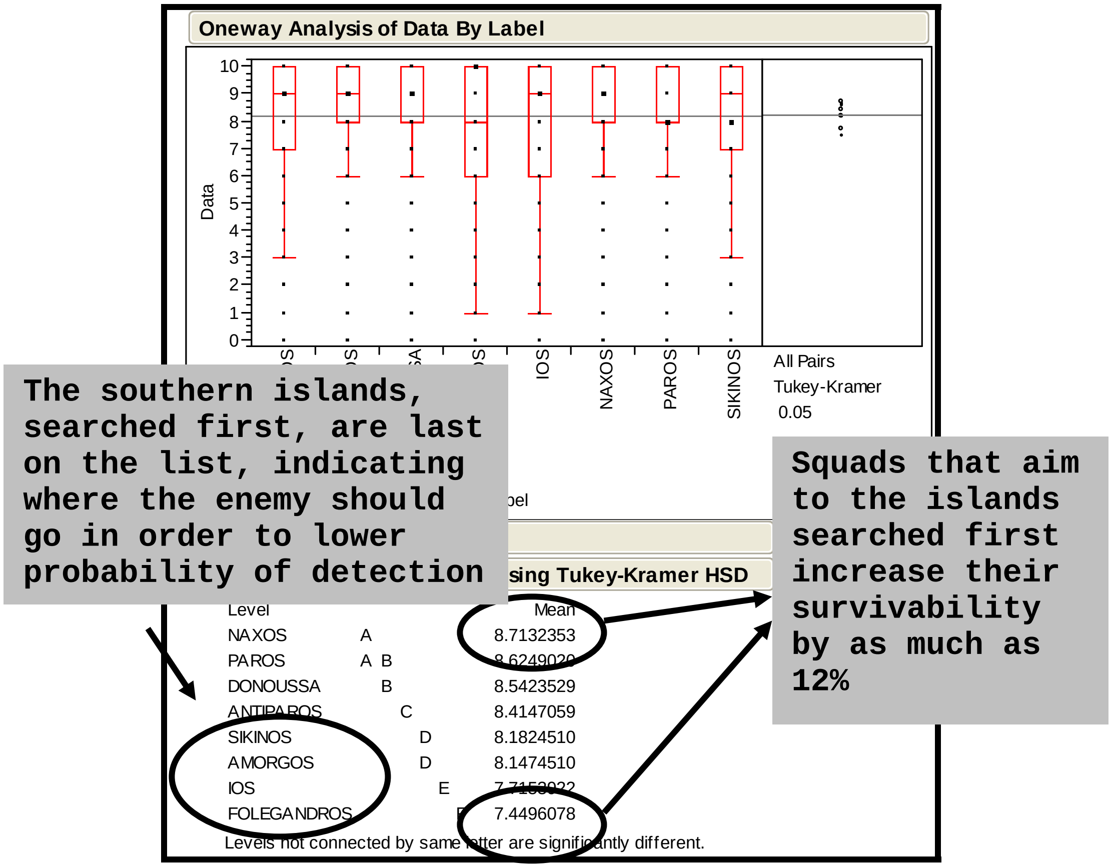


Figure 34. Comparison of detection means between the different enemy squads

A similar conclusion emerges when this MOE is examined by search patterns. The examination is necessary because different search patterns can yield different outcomes. An analysis of the "sector-modified" search pattern illustrates that the southern islands the VTUAV searches first are associated with the least number of detections. The divergence in number of detections between the southern and northern islands reaches up to 22% (Figure 35). Thus, though the "sector-modified" pattern may possess the highest rate of detection, the trade-off for speed is greater chance of enemy survival.

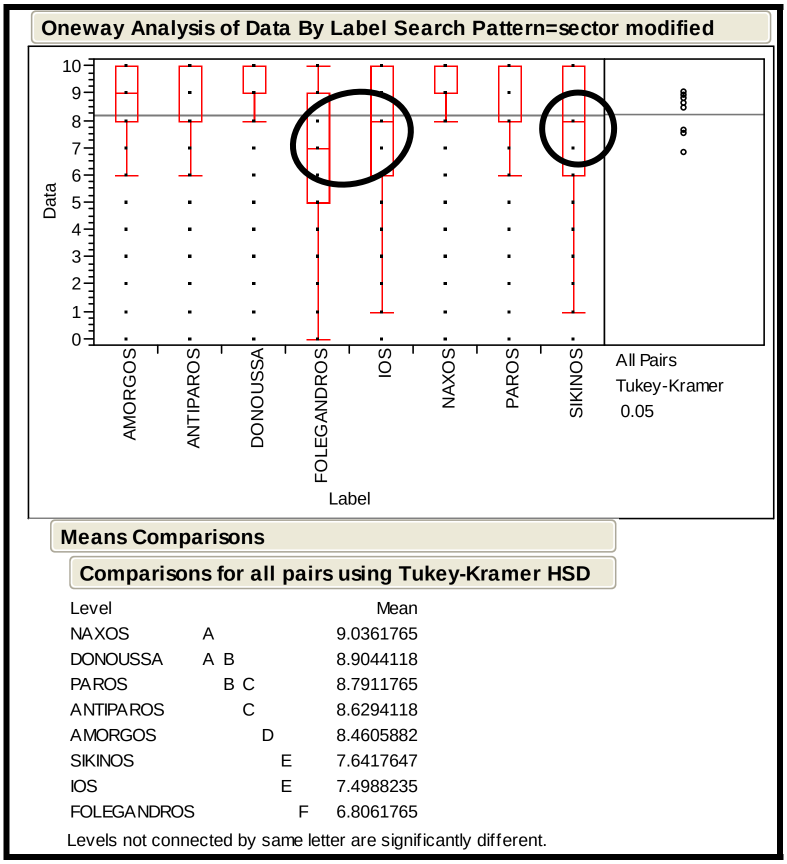


Figure 35. Comparison of detection means between the different enemy squads for the “sector-modified” search pattern

Analysis of the “parallel-modified” pattern reveals that the island of Amorgos has the least number of detections. This observation is explainable given that the VTUAV surveys this particular island only once, as it is on the edge of the search area. It is important to recognize that, overall, this covers the search area in a robust way. Figure 36 shows that the differences between squad detections are relatively small. In other words, if the VTUAV executes this pattern, then at every point in the search area it enjoys the same probability that it will find the enemy. The trade-off is that this search pattern is not time-efficient.

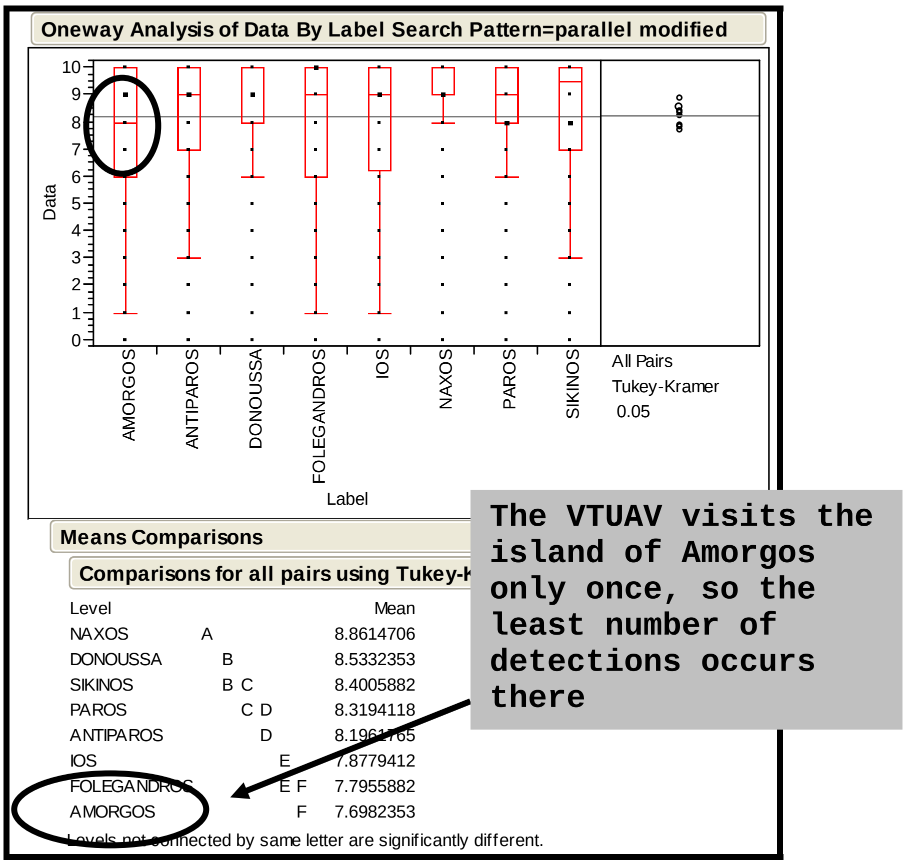


Figure 36. Comparison of detection means between the different enemy squads for the "parallel-modified" search pattern

The "spiral" search pattern revealed no considerable differences either. Like the "parallel-modified" search pattern, the "spiral" pattern seems to cover the area in a robust way. Figure 37 illustrates that the "spiral" search pattern is consistent in terms of squad detections. The pattern leaves no room for the enemy to outmaneuver the VTUAV.

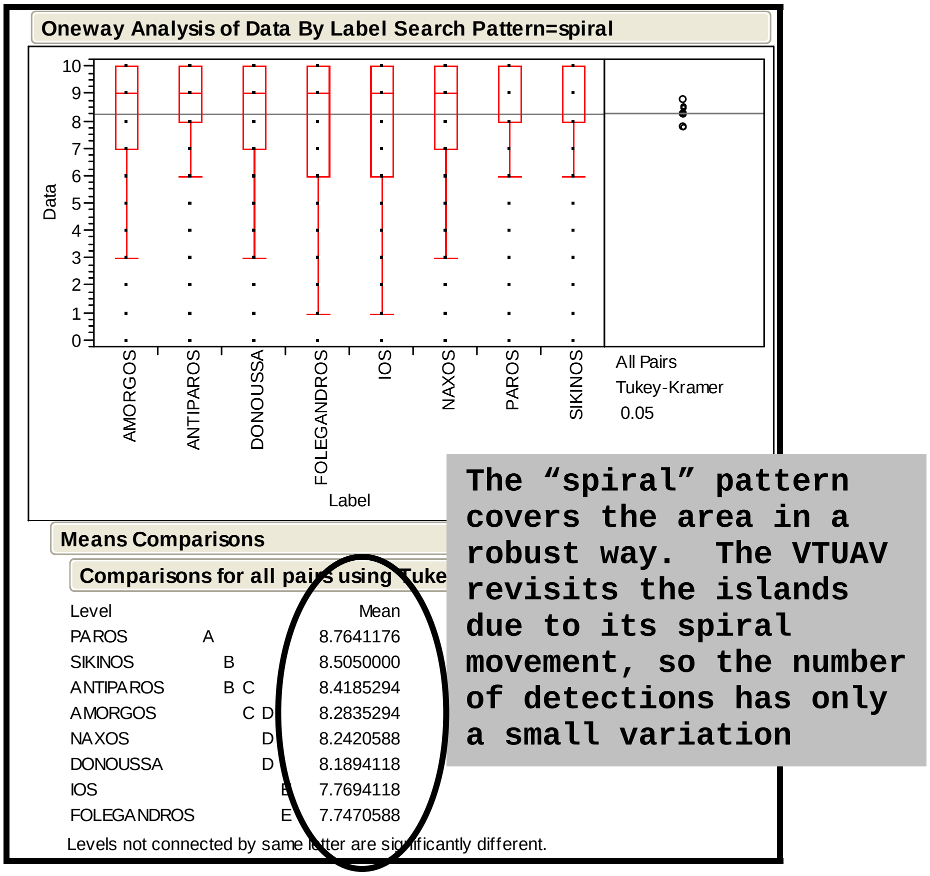


Figure 37. Comparison of detection means between the different enemy squads for the “spiral” search pattern

These means, sorted in ascending order and graphed, provide a helpful visual representation of the robustness of each search pattern relative to the others (Figure 38). The graph clearly expresses the shortcoming of the “sector-modified” pattern; while the pattern may yield exceptional results at some islands, it suffers a poor probability of discovering the enemy at others. The probability of detection varies from 0.68 to 0.90. Conversely, the other two patterns appear to be more efficient because the probability of detection varies less across the different squads.

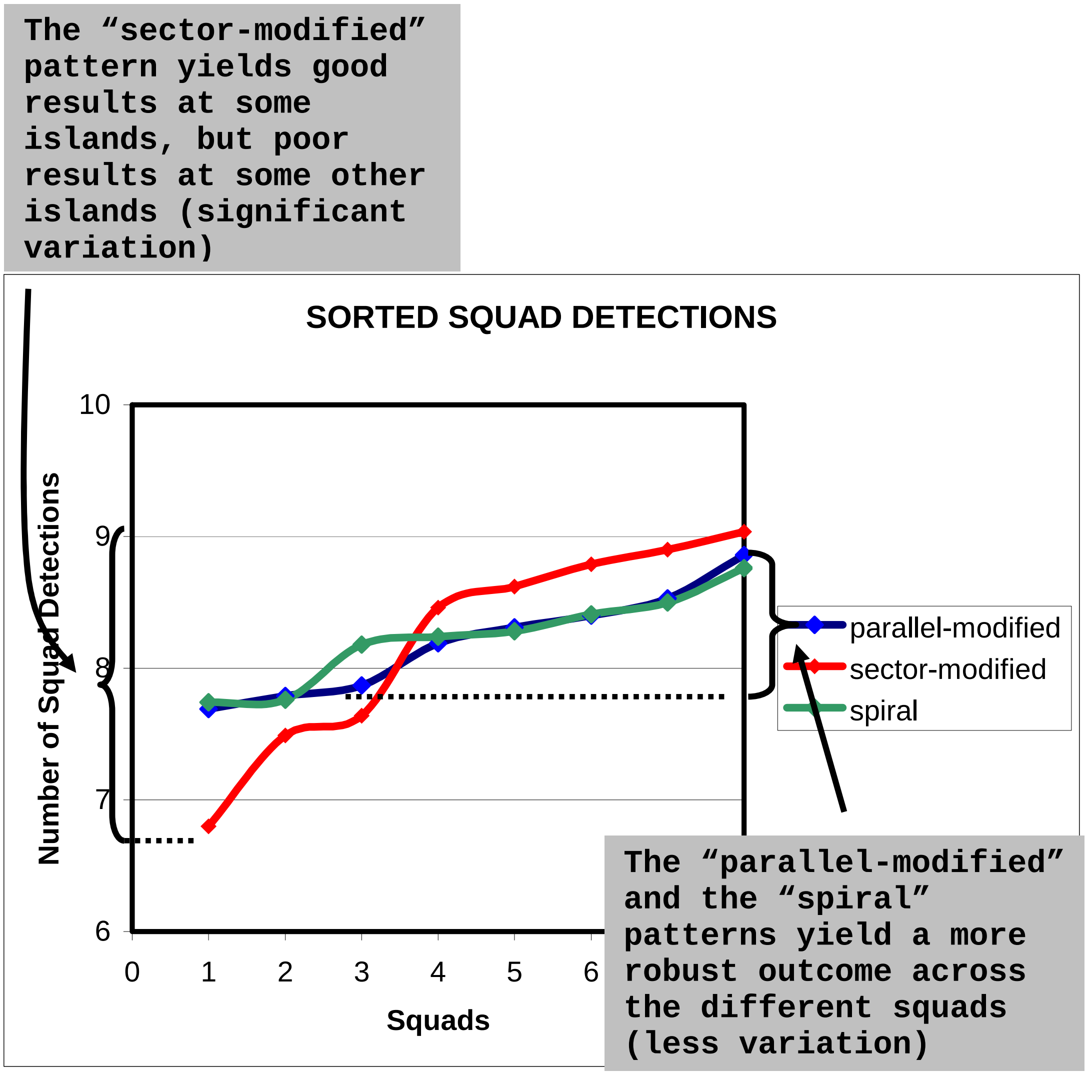


Figure 38. Robustness of the search patterns

2. Conclusions

a. For the VTUAV

Each of the three search patterns have different benefits and shortcomings. The “sector-modified” may operate as the fastest pattern, but it is not a robust one. In fact, it will be an ineffective search pattern if the enemy guesses the VTUAV’s movement. On the other hand, the other two search patterns are more robust, but not as time-efficient. This issue can be resolved easily if one understands the source of these patterns' strength. The "parallel-modified" and "spiral" patterns are more robust because the VTUAV revisits the islands it has already searched, as demonstrated in Figure 39. The VTUAV can combine the revisiting property of these patterns to a fast initial search in order to perform most effectively.

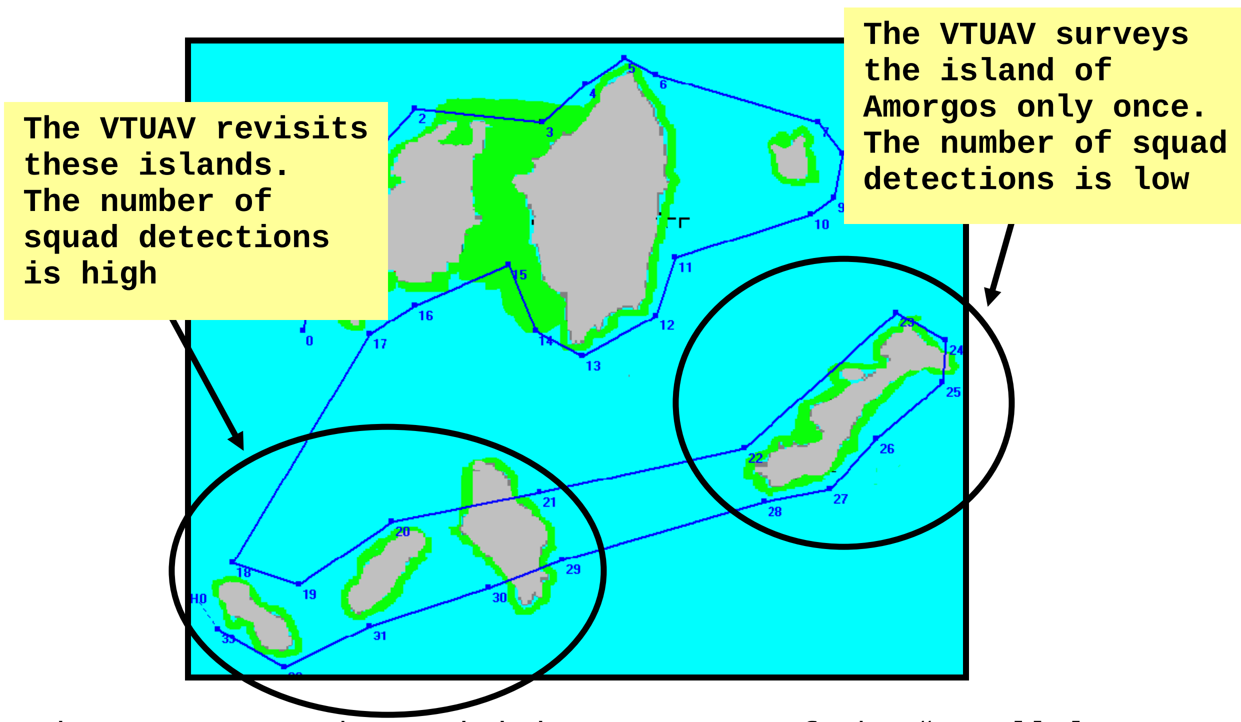


Figure 39. The revisiting property of the "parallel-modified" search pattern

It appears, therefore, that the Naval Commander need not deploy the VTUAV with any specific search pattern. The VTUAV's goal is to fly over all the islands in the fastest way and to revisit the first islands it searched, if not all the islands. The Commander can solve a TSP in order to determine the shortest path.

b. For the Enemy

The enemy increases its chances of survival if it aims its course to islands that that the VTUAV has searched first. This, of course, applies only if the enemy knows when the VTUAV commenced its search. If, for example, the enemy has a coordination and detection network at its disposal, as mentioned in the screening experiment analysis, then it could outmaneuver the VTUAV. Its survivability using better tactics increases by 12%.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The first screening experiment reveals the factors that are most important in the scenario and the way in which they interact with each other. Geography is a critical factor in terms of area size. While the island complexity does not affect the outcome of the search, it will affect the time required to achieve detection of the enemy. Since the VTUAV flies over all islands, the number of them is insignificant.

The VTUAV’s sensor range is critical as well. The industry should channel its efforts toward development in this area. On the other hand, although speed is important, extreme speed has no positive effect in the problem; this study suggests that present VTUAV platforms are adequate for use in search missions. The operational speed of the VTUAV should be neither too low or too high. Low VTUAV speed requires considerable ToT, whereas high speed risks the possibility that the enemy will get behind the VTUAV. Stealth is not an important factor, although it undoubtedly aids the VTUAV in other types of missions. The target processing capability is not important either. Most likely, a large expected detection range eliminates any effect from a possible delay in processing the targets.

The enemy’s technical features provide no major advantage to increase its survivability. If the VTUAV and the enemy meet, then there will be no escape. The enemy’s stealth and sensor range remain its biggest assets. Its survival depends almost entirely on its tactics. This study proposes some valuable courses of action designed to bolster evasion from the VTUAV. First, the enemy may coordinate its attacks with more than one vessel and establish an effective communications and detection network. Fishing vessels used as lookouts or coordination with troops on land could maximize the enemy's effort to remain undetected. Second, the enemy may promote a stepwise movement towards its objective. This island-to-island movement may allow the enemy to move behind the VTUAV. Like the VTUAV, the enemy's speed need not be high. In fact, high speed may increase the odds that the enemy moves into the VTUAV's path. Another disadvantage of a high-speed moving target is the likelihood that the VTUAV will consider it more suspicious and investigate it first.

This analysis clearly demonstrates that the three search patterns lead to the same outcome when time is not at stake. When time is important, which is usually the case, the "sector modified" search pattern is the most time-efficient for this situation. The most effective search does not depend on search pattern, but instead on the fastest way the VTUAV can visit all the islands. Therefore, if the geography permits, a Naval Commander should solve a TSP in order to find the fastest method of island inspection. The Naval Commander should also consider the possibility that the VTUAV may miss its target if the enemy aims toward the first islands in the search pattern. If only one VTUAV conducts the search, then the Commander should implement a revisiting policy in which the VTUAV flies over the first islands in the pattern again before returning to the mother ship.

If the enemy already inhabits an area that a VTUAV will search, then that enemy should react boldly. The analysis suggests that the enemy increases its chances of avoiding detection if it aims to the first islands the VTUAV searched. If the VTUAV does not revisit the islands, the enemy can avoid discovery. A coordination and detection network could provide vital information to the FPB and assist its maneuvers.

B. FUTURE RESEARCH

After these conclusions, several potential research topics surface for both the VTUAV deployment and the enemy. A brief discussion about them is as follows:

- It is reasonable to say that greater numbers of VTUAVs increase the speed of a search. Is there an effective way or configuration for their deployment? One might argue that two VTUAVs should be deployed simultaneously, while another might maintain that a deployment in waves would be more effective.
- It would be helpful to a decision maker to have simple decision tools like the plots in Figures 24 and 25. What should these tools look like? Is it possible to generate them in a way that they represent more general cases?
- What configuration should an effective enemy coordination and detection network have? Are there any countermeasures that the Naval Commander could bring into play? What would the impact be of such a network to the VTUAV’s mission?

C. EPILOGUE

This study revealed the main effects and interactions in a search operation. It further explored some search patterns in order to find effective naval tactics for both friendly and enemy forces. The focus area for development of the VTUAV is more on its technology than on the tactics with which it operates. The enemy’s priorities lie in the opposite direction; the focus area is more on tactics than on technology. The VTUAV depends on equipment and the enemy on seamanship and intuition. It is a battle between man and machine. But this has always been the story of war.

> "Wars may be fought with weapons, but they are won by men."
>
> George Patton

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